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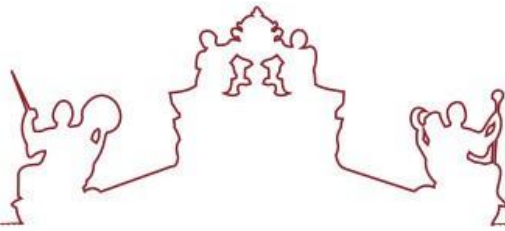Mestrado em Biologia da Conservação

Dissertação

Prioritizing areas for nature conservation under climate change: Iberian Peninsula as a case-study

Inês Sofia Gonçalves Pereira

Orientador(es) / Diogo André Alagador

Évora 2022

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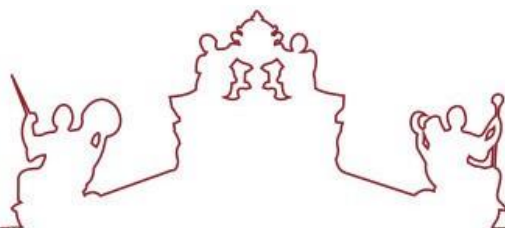Mestrado em Biologia da Conservação

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A dissertação foi objeto de apreciação e discussão pública pelo seguinte júri nomeado pelo Diretor da Escola de Ciências e Tecnologia:

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Prioritizing areas for nature conservation under climate change: Iberian Peninsula as a case-study

Abstract

The increased biodiversity loss led the European Union to create an ecological network of protected areas, Natura 2000 Network, to ensure the long-term survival of the most vulnerable species and their habitats. European governments have also invested in conservation with the allocation of formal protected areas. Another threat is climate change, which already affected species distributions and phenology. One of the main mitigation strategies is the expansion of protected areas and ecological corridors. This study aims to analyse and identify climate-resilient areas in Iberian Peninsula in order to maximise biodiversity persistence and verify if those areas match Iberian protected areas. I identified the areas likely to sustain adequate climate conditions for nine species of vertebrates (two mammals, three amphibians and four reptiles) considering three scenarios of global climate change. By answering this question, area-based conservation measures can be applied to those species, based on ecological criteria and following the predictions for climate change.

Keywords: protected areas, suitability, corridors, climate adaptation, dispersal.

Priorização de áreas para a conservação da natureza sob alterações climáticas: Península Ibérica como um caso-estudo

Resumo

O aumento da perda de biodiversidade levou a União Europeia a criar uma rede ecológica de áreas protegidas, a Rede Natura 2000, para garantir a sobrevivência a longo prazo das espécies mais vulneráveis e dos seus habitats. Os governos também investiram na conservação com o estabelecimento de áreas protegidas. Outra ameaça são as mudanças climáticas, que já afectaram a distribuição de espécies e fenologia. Uma das principais estratégias de mitigação é a expansão de áreas protegidas e corredores ecológicos. Este estudo tem como objetivo analisar e identificar áreas de conservação resilientes às alterações do clima na Península Ibérica, de forma a maximizar a persistência da biodiversidade e verificar se estas áreas coincidem com as áreas protegidas da Península Ibérica. Identifiquei as áreas que podem sustentar as condições climáticas para nove espécies de vertebrados (dois mamíferos, três anfíbios e quatro répteis) considerando três cenários de mudanças climáticas globais. Ao responder a esta questão, podem ser aplicadas a estas espécies medidas de conservação com base em critérios ecológicos e seguindo as previsões de mudanças climáticas.

Palavras-chave: áreas protegidas, adequabilidade, corredores, adaptação climática, dispersão.

Introduction

The concerns about the environment had their start in the early '70s, with the improving living conditions of people around the world and the disparities between industrialized and developing countries. It was a matter of time to understand that it was not possible to develop infinitely without considering the environment.

The increased degradation of the ecosystems ended up leading to an international response, and the first World Summit on the Human Environment focusing on international environmental issues was held in Stockholm, in 1971 (Nations, n.d.). Many other conventions happened in the same decade (for instance, Ramsar Convention, Bern Convention, among other), pointing out the main pressures on the marine and terrestrial ecosystems: land-use change, pollution, over-harvesting and the introduction of alien species, all from human activities (Secretariat of the Convention on Biological Diversity, 2003, pp. 1–2). The urgency in conserving wildlife and their habitats, and the need to put forces together through global environmental policies, drove the European Union (EU28) to create an environmental law to be adopted by all its member states. In 1979, the EU28 Birds Directive 79/409/EEC was created. The Directive is a legal tool to conserve wild migratory and endangered bird species occurring within the EU28, as well as their habitats. The most suitable habitats for those species are incorporated in so-called Special Protection Areas, which are subjected to land use restrictions and dedicated conservation efforts: the member states are obligated to take necessary measures to maintain EU28 [bird] populations "at a level which corresponds in particular to their ecological, scientific and cultural requirements" (Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the Conservation of Wild Birds, n.d.).

At the time, the efforts to stop the loss of biodiversity were focused on the conservation of a few species. But during the 1992 Rio Earth Summit, the Convention on Biological Diversity (CBD), established by the United Nations Environment Programme (UNEP) (Unit Biosafety, 2021), required the signatory parties to commit to "establish a system of protected areas or areas where special measures need to be taken to conserve biological diversity" (United Nations, 1992, p. 8). The EU28 had already given a few steps in wildlife conservation based on protected habitats, through Birds Directive, and during the same year of the CBD signature, the UE adopted a new directive, the Council Directive 92/43/EEC, the Habitats Directive. This Directive points to the designation of Community Importance Sites (SCIs), core areas of habitats of listed species to protect, that "must be managed under the ecological needs of the species" (The Habitats Directive - Environment - European Commission, n.d.). In 1994, all protected areas (PAs) designated by Habitats and Birds Directives were included in a new ecological network of PAs, the Natura 2000 Network, N2k (The Birds Directive - Environment - European Commission, n.d.), whose revision and monitoring were carried until a final area

designation, by the year 2000. The N2k aims to ensure the long-term survival of the most vulnerable species listed in the annexes of both directives and habitats therein. It includes all important areas for species persistence, not only the core breeding areas, but also resting sites. The N2k forms the foundation of a coordinated EU 28 biodiversity policy and is the main tool for nature conservation. Currently, it is the largest network of PAs worldwide, including over 18% of the EU28's land area and more than 8% of the EU28's marine area and it is seen as the most ambitious EU 28's biodiversity policy (Natura 2000 - Environment - European Commission, n.d.).

Meanwhile, the degradation of ecosystems and biodiversity loss was aggravated by another global issue: climate change. Although the history of climate change science goes back to the 19th century, the debate began to take shape in 1988 during the Toronto Conference on the Changing Atmosphere: Implications for Global Security. The enhanced greenhouse effect due to the increase of polluting gases emissions led to a greater concern about the possibility of a changing climate by anthropological causes (Houghton et al., 1990). Because the scientific evidence about the impacts of climate change was scarce, the Intergovernmental Panel on Climate Change (hereafter IPCC) was established by the UNEP and the World Meteorological Organization in 1988. The aim was to provide policymakers with cross-sectorial scientific assessments about climate change impacts and settlement of mitigation strategies (Houghton et al., 1990). In 1990, the first worldwide scientific assessment on climate change was published by the IPCC (Houghton et al., 1990). The reports therein assure that the human activity emissions were increasing carbon dioxide, methane, chlorofluorocarbons and nitrous oxide concentration in the atmosphere, thus enhancing the greenhouse effect. It also stated concerns about the intensification of this effect, resulting in the additional warming of the Earth's surface and warned that the more gas emissions increase, the greater reduction will have to occur for concentrations to stabilize (Houghton et al., 1990). During the fifth meeting of the Conference of the Parties to the CBD in 2000, the risks of biodiversity under climate change were first highlighted, especially the ones directed to forest ecosystems. Although most of biota were affected by climate change during the Pleistocene (fluctuations in the temperature, carbon dioxide concentration in the atmosphere, precipitation…), the necessary adaptations of species through range shifts have occurred across a non-fragmented landscape and with little or no anthropogenic pressure (Secretariat of the Convention on Biological Diversity, 2003). Nowadays, the scenario is widely contrasting. The Secretariat of the CBD (Technical Series No. 10) in 2003 launched a report about the interlinkages between biodiversity and climate change, where the effects of climate change over the timing of reproduction of animals and plants, migration of animals, lengths of growing seasons, species distributions, population size, genetics and dynamics, the frequency of pest and disease outbreaks and the widespread of invasive species were highlighted (Secretariat of the Convention on Biological Diversity, 2003). At a time when the ecosystems are already

under threat, the impacts of current climate change on the biodiversity and their associated livelihoods are alarming. Vertebrate species are responding to climate change by shifting geographical distributions into more suitable areas (Hickling et al., 2006; Parmesan, 2006), but with the land use change and fragmented habitats, many species have their potential habitats reduced and their capabilities to track better climate conditions undermined.

One of the main tools to overcome this issue are area-based conservation measures. The CBD recognizes that conserving global biodiversity against the backdrop of climate change and other anthropogenic factors passes by increasing the resiliency of existing PAs through effective management, their judicious expansion into ecologically functional areas and the reinforcement of connectivity among them (Secretariat of the Convention on Biological Diversity, 2003). As pointed out by the report of the Secretariat of the CBD in 2003, networks of PAs with connecting corridors provide conditions to dispersal and migration for plants and animals: "The placement and management of reserves (…) will need to take into account potential climate change (…). Options include corridors or habitat matrices that link currently fragmented reserves and landscapes to provide the potential for migration.". These areas have to gather a set of climate conditions adequate for the species/populations to move without resistance and are being commonly referred as a solution (Herrmann et al., 2016; Nuñez et al., 2013). This strategy began to have such importance that during the tenth meeting of the Conference of the Parties to the CBD, one of the targets of the Strategic Plan for Biodiversity 2011-2020 was that by 2020, at least 17% of terrestrial and inland water had to be conserved through connected systems of PAs (Aichi Target 11). This target was not fulfilled by most of the countries and the ineffectiveness of conservation policies is still heightened by the low functional value of most of the existing PAs.

CBD targets for area-based conservation are being redefined, with the expansion of PAs to 30% of land and sea, with a third of that area strictly dedicated to biodiversity conservation. These numbers result from the observation that climate change increases the dynamics of biodiversity in space, leading to the need to impose more demanding targets and allowing more flexible area-based solutions. The EU28 has already launched the Biodiversity Conservation Strategy to 2030, as a central issue of the Green Agreement (European Commission, Directorate-General for Environment, 2021). However, in this new policy agenda for biodiversity conservation, other land management policies will be essential to provide quality areas for biodiversity to thrive in unprotected landscapes (e.g., offsetting regulations, agreements with landholders, land banking, among others). Both crises of climate and biodiversity are being treated in global and European policy platforms. The recent UN COP16 (held in Glasgow, October 2021) reinforced the need of nature-based solutions as an important mean to expand carbon sequestration. Matching vegetation types (herbs, shrubs and trees) with

local biogeographical history, the protection of old-growth forest, a heterogeneous forest succession, afforestation of degraded areas, the promotion of soil biodiversity and its organic content are some of the measures to take into consideration such to boost carbon retention worldwide while promoting a healthy nature.

The Secretariat of the Convention on Biological Diversity, (2014) states that there is little information regarding trends of ecosystems vulnerable to climate change. This study may contribute to providing some highlights towards this lack of information for the Mediterranean ecosystem and specifically, the Iberian Peninsula. This study looks to take a different analytical viewpoint into the identification of climate-resilient conservation areas for maximisation of biodiversity persistence. It departs from a new concept in conservation planning (the climate adaptive corridor) (Alagador et al., 2014a) to identify in the Iberian Peninsula (IP) the areas likely to sustain climate conditions for a pool of nine vertebrate species to endure three scenarios of climate change up to 2080. The study pretends to answer the following questions:

1. In what periods of time there is a need of greater investment against changes in climate in the IP?
2. In which areas a higher number of adaptive corridors will converge to?
3. What are the predicted temporal trends in suitable climates for each species at several geographical scales (EU28, IP, Iberian PAs, current species locations in IP and adaptive corridors)?
4. How are adaptive corridors characterized using several landscape descriptors and at what level they coincide with existing PAs?

By answering these questions, this study aims to provide a brief quantified overview of potential areas where more conservation focus is needed. The results that will be provided here were developed under a biogeographic macro-scale view. Therefore, they still need to go through several stages of validation, with increasing stakeholder intervention while going into more local scales. The link between researchers, policymakers, landowners and civil society is a way to pressure current socio-economic governance - framed in unlimited development - to shift towards sustainable development which better promotes welfare for the present and future generations and, at the same time, the equilibrium of the planet.

Materials and Methods

Species selection

The analysis focuses on a small set of vertebrate and plant species listed as threatened, whose geographical distributions converge, to a large extent, in the IP.

First, I pre-selected all terrestrial vertebrates and plant species with a European distribution among EU28 (i.e., 27 member states of the European Union plus United Kingdom) listed in the Habitats and Birds Directives. These two regulations point to a systemic planning of conservation action at the EU28 scale. I restricted the selection of plants to the arboreal species listed in priority forest habitats in the Habitats Directive (Annexe I), given their relevance as basal structures sustaining mature natural habitats: temperate; Mediterranean deciduous; Mediterranean sclerophyllous; alpine and subalpine coniferous, and Mediterranean mountainous coniferous forests. Among the initial set of terrestrial vertebrate species, the ones facing a high risk of extinction and requiring urgent conservation responses were selected (i.e., listed as near threatened, vulnerable, endangered or critically endangered in the European Red List from the International Union for the Conservation of Nature (IUCN), or if lacking, in the Global IUCN Red List (Annexe I).

At this stage, 60 species were considered. In order to highlight groups of species with similar geographical range patterns at EU28 scale, I performed a cluster analysis using range data obtained from the European Atlases (Plants: Jalas & Suominen, (1995); Birds: Keller et al., (2020); Reptiles and Amphibians: Mitchell-Jones et al., (1999)). These data encompass presence and absence records of each species in 50 km x 50 km grid cells. To increase the robustness of the analysis, I obtained multiple clustering solutions applying distinct clustering algorithms (agglomerative: Complete-linkage, Average-linkage, Ward's minimum variance method, and divisive: DIANA) and different similarity metrics appropriate to handle presence/absence binary data (Sørensen-Dice dissimilarity index and Jaccard similarity index), using the function *"vegdist"* in the R-CRAN Version 4.0.5 (https://cran.r-project.org/) package "*vegan*" (Oksanen et al., 2019) (version 4.0.5). The 20 clustering solutions obtained were aggregated using an ensemble procedure using the "*cl_ensemble*" function in package "*clue*" (Hornik, 2005), which measures cluster agreements (through Euclidean distances) among the input solutions. That is, it counts the frequency that every pair of species are clustered at each hierarchical level (Alqurashi & Wang, 2019). The ensembled solution represents the one that best integrates the clustering variability obtained from the 20 initial clusters (Fig. 1 Annexe II). The largest clustering stability was defined by seven groups of species. From these, I selected the one whose species' distributions are concentrated in (but not limited to) the IP. This region is one of the southern European peninsulas that served as climate refugia in the Last Glaciation (aprox. 14,000 years bp) and one of the regions predicted

to undergo large climate shifts (Taberlet et al., 1998). The study of the adaptive responses of the species that integrate this group can serve as general indicators of the species adaptive responses of climate change that will occur in south Europe. This final group includes nine species: three amphibian, four reptile and two mammal species (Table 1).

Species dispersal

Climate change impacts may result in changes in species distribution patterns, as an adaptive response. The ability to colonize new areas and track suitable habitat shifts requires long distance dispersal events (Boeye et al., 2013; Ronce, 2007; Tamme, 2014; Trakhtenbrot et al., 2005), which depends on species' dispersal capacity. For most species, there are no accurate data on dispersal abilities, as these depend on landscape features, habitat quality, time of year, intra and interspecific interactions, among other factors and the interaction between them. To overcome this analytical constraint, life-history traits (generation length and diet type), morphologic traits and taxonomic proximity are therefore used as proxies (Angert et al., 2011).

I estimated maximum dispersal distances of mammal species based on the allometric formulas described by Sutherland et al., (2000) (Annexe III). These formulas characterize the maximum distance covered by single-natal events, using adult body mass and diet type (carnivore or not) as predictors. Adult body masses and diets were obtained from Tacutu et al., (2013) and IUCN, (2011), respectively. Information of *Microtus cabrerae*, derived from Pita et al., (2014).

For amphibians, data characterizing dispersal of *Chioglossa lusitanica* were obtained from a life-history amphibians database (Trochet et al., 2014). The absence of information for *Pelobates cultripes* and *Rana iberica,* even for closely related species, implied the use of a general approach proposed by Fortuna et al., (2006), where dispersal capacities of toads and frogs were settled as 1000 m and 500 m, respectively, underpinned by Smith & Green, (2005) broad set of amphibian dispersal distances. The maximum dispersal distance for *Lacerta schreiberi* was based on a closely related species (*L. agilis*) and on allometric relationships using snout-vent-length (SVL), the most common measure used as determinant of movement ability in lizards (Jenkins et al., 2007; Popescu, et al., 2013). Because there are no studies respecting *Chalcides bedriagai*, *Iberolacerta monticola*, *Mauremys leprosa*, or closely related species (at the family-level), the maximum dispersal distance of these species was settled as the average dispersal distance for reptiles as presented by Henle et al., (2008): 1000 m.

The temporal dimension of dispersal distances is not directly considered in the used models or databases. Major dispersal events of mammal and amphibian species usually takes place before first reproduction (during the first year of life) (Sutherland et al.,

2000) but in lizard species, dispersal is a highly plastic adaptive response to different selective pressures (abiotic, biotic and social environment) (Vercken et al., 2012). I considered one year as the time respecting the dispersal events of all species described above (see Table 1). This decision included the reptiles, since the dispersal values corresponded in magnitude to the amphibian's dispersion values.

Table 1 The species under analysis, their abbreviation name, common name, taxonomic class, conservation status (IUCN Red List of Threatened Species. Version 2009) and maximum dispersal distance (Max dist). Status: VU-Vulnerable; NT- Near Threatened. The last three columns refer to species range data and modelling performance. Iberian range refers to the number of 10 km x 10 km grid cells and respective percentage-area of Iberian Peninsula; EU28 range refers to the number of 50 km x 50 km grid cells and respective percentage of the whole European Union; model accuracy refers to the minimum and maximum True Skill Statistic (TSS) values obtained in the ensemble framework used to predict species climatic suitability scores at the EU28 scale.

Species (abbreviation)	Species (common name)	Class	Status	Max dist (km/yr)	Iberian range (10x10)	EU28 range (50x50)	Model accuracy TSS
Chioglossa lusitanica (Clu)	*Golden-striped Salamander*	Amphibian	VU	0.70	342 (5.8%)	38 (1.7%)	0.737-1.000
Pelobates cultripes (Pcu)	*Western Spadefoot*	Amphibian	NT	1.00	1675 (28.2%)	197 (8.6%)	0.688-0.905
Rana iberica (Rib)	*Iberian Frog*	Amphibian	NT	0.50	719 (12.1%)	63 (2.8%)	0.703-0.975
Mauremys leprosa (Mle)	*Mediterranian Turtle*	Reptile	VU	1.00	4506 (76.1%)	134 (5.9%)	0.530-0.745
Iberolacerta monticola (Imo)	*Iberian Mountain Lizard*	Reptile	VU	1.00	127 (2.1%)	123 (5.3%)	0.852-0.966
Lacerta schreiberi (Lsc)	*Iberian Emerald Lizard*	Reptile	NT	2.00	825 (13.9%)	80 (3.5%)	0.488-1.000
Chalcides bedriagai (Cbe)	*Spanish Cylindrical Skink*	Reptile	NT	1.00	701 (11.8%)	23 (1.1%)	0.471-0.666
Galemys pyrenaicus (Gpy)	*Pyrenean Desman*	Mammal	VU	0.50	604 (10.2%)	73 (3.3%)	0.626-0.967
Microtus cabrerae (Mca)	*Cabrera's Vole*	Mammal	NT	0.46	453 (7.6%)	58 (2.5%)	0.645-0.931

Climatic suitability data

Climatic suitability data for species were provided from unpublished work. The climate variables used to estimate the local (i.e., grid cell) climatic suitability for each species in four time periods (a baseline period equivalent to 1990 and 30 year periods centred in 2020, 2050 and 2080) were mean annual temperature; temperature seasonality; maximum temperature of the warmest month; minimum temperature of the coldest month; mean annual precipitation; total precipitation of the wettest month; total precipitation of the driest month; and precipitation seasonality. These variables are presumed to be important in driving range variation of terrestrial vertebrate species at biogeographic scales (Li et al., 2016).

For each species, climate data were related with occurrence records using a set of species distribution models and suitability values were obtained from ensembles of these models, based on their predictive performance in current time (see Araújo et al., 2011, for details about the framework followed, and Table 1 for descriptors of species range sizes and modelling accuracy). Suitability scores define a gradient from zero to one, with one representing the areas with the largest suitability based on local climate. Within the scope of data presentation, all values presented refer to the suitability scores multiplied by 1000. Climate suitability of each species was projected into 10 km x 10 km grid cells for the whole EU28. In Figure 1 is present the climate suitability of each species and their distribution in the IP.
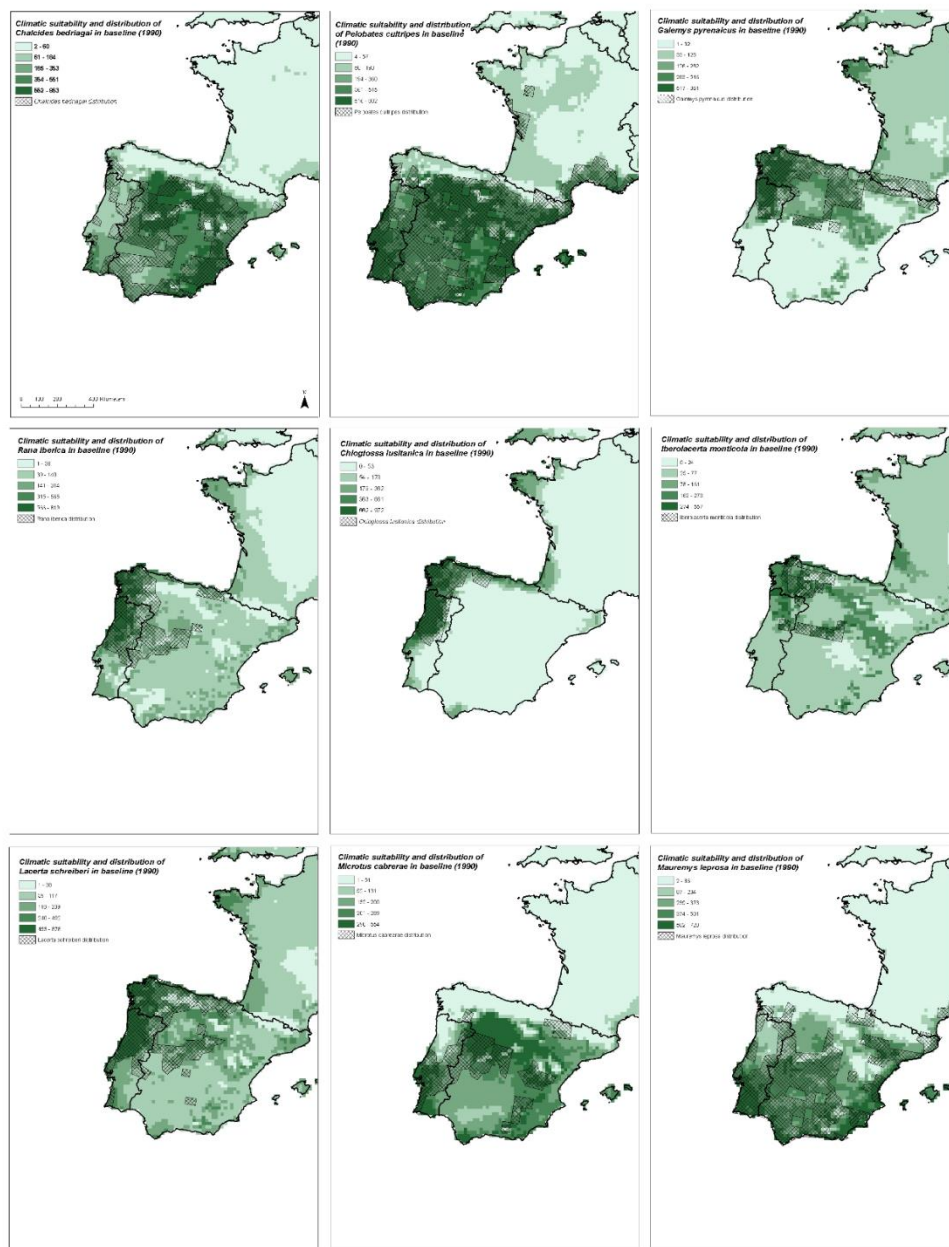

Figure 1 Climatic suitability values and distribution of each species in baseline period in the Iberian Peninsula (1990).

Various climate models were used to build species-specific climatic suitability scores in EU28 through time, aggregating a set of different information that deals with uncertainty in the way climate is presumed to unfold in the future. Predictions were settled based on three Representative Concentration Pathways (RCP) related with future climate scenarios, defined by the IPCC from the fifth assessment report (AR5) (Pachauri et al., 2014): RCP 4.5, RCP 6.0, RCP 8.5. Each scenario defines different pathways of human development based on population size, economic activity, lifestyle, energy use, land use patterns, technology and climate policy. These paths are projected to have different impacts in GHG emissions and atmospheric concentrations, air pollutant emissions and land use.

There is no consensus on what is the most plausible RCP at medium to long-terms and therefore the one most likely to drive biodiversity impacts. As socioeconomic decisions are hard to model with precision and because of the multiple complexities of relationships within the climate system, huge uncertainty exists when considering the most probable climate change trajectory. I chose to undertake analyses for each of the most probable RCPs (RCP 4.5, RCP 6.0, RCP 8.5), but focusing the main assessments on RCP 6.0, an intermediate approach recently pointed as the trajectory more aligned with recent climate trends (Hausfather & Peters, 2020). Although RCP 8.5 is widely used in the literature, it is an extreme worst-case scenario, for which worldwide policies are trying to abate. The assumption that society will not impose any climate mitigation measures is already incorrect (Riahi et al., 2011). Furthermore, the widespread use of this scenario is being contested by many authors, with some recent studies pointing out that RCP 8.5 is becoming increasingly implausible (Burgess et al., 2020; Hausfather & Peters, 2020; Ho et al., 2019; Pielke & Ritchie, 2020).

Study area

Study area boundaries were defined by the species occurrence areas in the IP plus the terrestrial area covered by the maximum dispersal among species (*Dmax*=2 km/year) over a 90-year range period (from the baseline period to 2080), 180 km total. Final area therefore extents to southwestern France and PAs within (Fig. 2). I considered the Portuguese, Spanish and southwestern France nationally established PAs included in the I-IV IUCN categories, as these are presumed to be the ones with the highest mandates to protect biodiversity therein. The sites listed in Natura 2000 network (N2k) were also considered because they contain habitats and species considered critical to conserve by EU28 member states. The georeferenced information was provided by Alagador et al., (2021) at 10 km x 10 km grid cell resolution for the whole EU28. Boundaries of national PAs were downloaded from the World Database on Protected Areas website (available

at https://www.protectedplanet.net/; date: 7 March 2019) and N2k data were obtained from the European Environment Agency (available at https://www.eea.europa.eu/data-and-maps/data/natura-11; date 7 March 2019). I obtained the coordinates of the study area (hereafter IP, for simplification) using ArcMap 10.0 (Projected Coordinate System: ETRS_1989_LAEA) and the R-CRAN Version 4.0.5 (https://cran.r-project.org/) package *"foreign"*. I calculated the fraction of each grid cell covered by PAs, using ArcMap 10.0 and R-CRAN packages *"raster" and "rgdal"*. Species-specific climate suitability in PAs of each grid cell was obtained by the product of grid cell suitability score with the fraction of PA within it.
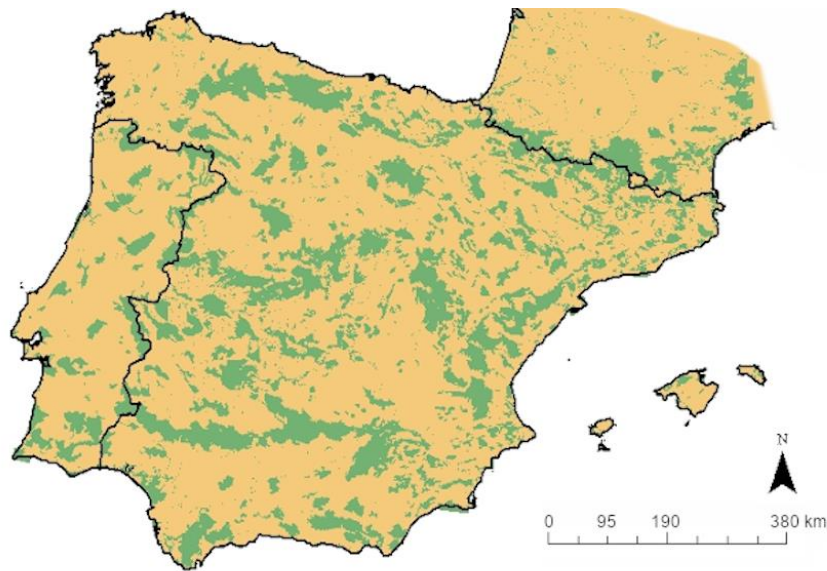
Figure 2 Study area map: Iberian Peninsula (Portugal, Spain and Balearic Islands) and southwest France. Green areas indicate the location of protected areas (national and N2k).

Climate adaptive trajectories

The climate adaptive trajectories (hereafter corridors) that provide the best trajectories to areas of highest suitability for each species were identified using the software iC5 (*Climate Change Concerned Conservation Corridors: an identifier*) (https://zenodo.org/record/3932003#.YaJfKFBUn2A). This software is used for the identification of the areas where species persistence is maximised over time (Alagador & Cerdeira, 2020). The persistence of a species in a corridor is established using the product of climate suitable scores of grid cells over time with the product of probabilities of successful colonization between two consecutive cells in the corridor. These dispersal probabilities are obtained by

$$exp(-\alpha . \frac{D}{Dmax}),$$

where *Dmax* is the maximum dispersal ability of a species in 30 years-time, *D* is the distance between the source and target grid cells (measured in *Dmax* units) and *α* defines the rate of decay of successful dispersal between any two consecutive grid cells in 30 years-time, as defined by Alagador & Cerdeira, (2018). The *α*-parameter was obtained based on the subjective assumption that the successful probability at *Dmax* is 0.5 for species with the lowest dispersal abilities (<16 km) and 0.2 for species with the highest dispersal abilities (>16 km). This approach alludes to an uncertainty regarding the success of species with less dispersal capacities (Table 2 and Fig. 3).

Table 2 Input parameters to model the climatic adaptive trajectories of each species

Species	Dmax (km)	Pr(Dmax)	α
Chioglossa lusitanica	21	0.2	1.6094
Pelobates cultripes	30	0.2	1.6095
Rana iberica	15	0.5	0.6931
Mauremys leprosa	30	0.2	1.6094
Iberolacerta monticola	30	0.2	1.6095
Lacerta schreiberi	60	0.2	1.6096
Chalcides bedriagai	30	0.2	1.6097
Galemys pyrenaicus	15	0.5	0.6931
Microtus cabrerae	14	0.5	0.6931

For each species, I obtained the 500 corridors with the highest persistence assuming each of the three RCPs. The iC5 software allows to control the maximum number of corridors converging in any grid cell in each time period. Here, I settled the convergence parameter to 500, which does not constrain the convergence among adaptive trajectories of each species (see Alagador et al., (2021) for explanation). In these cases, probabilities of successful colonization are maximum, with persistence relying solely on local suitability values.
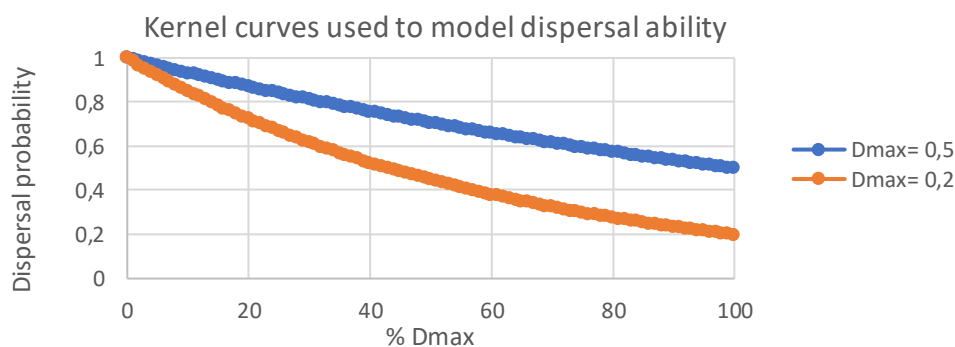
Figure 3 The kernel curves modelled the dispersal ability of each analysed species in a 30-year period as a function of the Euclidean distance between a source and a terminal cell. Dmax represents the probability of successful colonization when source and target areas are at the maximum dispersal distance for a species. The blue line represents the dispersal probability of *Galemys pyrenaicus, Microtus cabrerae* and *Rana iberica*. The orange line represents the dispersal probability of *Pelobates cultripes, Chalcides bedriagai, Chioglossa lusitanica, Mauremys leprosa, Lacerta schreiberi* and *Iberolacerta monticola*.

Landscape descriptors

I characterized the study area based on four distinct indicators that assess different landscape properties and may impact species adaptation: land use, anthropic pressure on the environment, topography and carbon retention.

I obtained land use classes from Corine Land Cover (CLC) 2018 (available at https://land.copernicus.eu/pan-european/corine-land-cover/clc2018; date: 8 August 2021). This dataset includes 44 land-use classes in raster format, with a spatial resolution of 25 ha. I selected and grouped the ones that I considered more relevant for the present study (artificial surfaces; green artificial structures: green urban areas and sport and leisure facilities; homogeneous agriculture - only one type of production dominates, heterogeneous agriculture - a mosaic of different agricultural and forestry productions in the same area; forests and semi-natural land, and; continental waters). I built a map with the percentage of each land use in each 10 km x 10 km grid cell in the IP, using ArcMap 10.0 (Projected Coordinate System: ETRS_1989_LAEA).

Data regarding human pressure on the environment were obtained from https://sedac.ciesin.columbia.edu/data/set/wildareas-v3-2009-human-footprint/data-download: date: 29 July 2021. These data provide a global map of cumulative human pressure on the environment in 2009, at a spatial resolution of 1 km2. The Human Footprint index (HF) was generated based on built-up structures, population density, electric power infrastructures, croplands, pasture lands, roads, railways and navigable waterways, integrating drivers of local disturbance. The index can be used as a proxy for human disturbance over natural systems. The HF ranges from 0 to 50, in an increasing scale of disturbance (Venter et al., 2016a, 2016b). I created a map with the average HF index in each 10 km x 10 km grid cells of the IP, using software ArcMap 10.0.

A measure of roughness at 25 m resolution was collected from a Digital Elevation Model for Europe (https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem). Roughness is related to topographic complexity and solar exposure. Therefore, it can be used in climate change impact assessments over biodiversity, as areas of large topographic variability allow species to find micro-scaled climates without needing to undergo large movements over landscape (e.g., micro-refugia). I undertook statistics in raster (Arcmap 10.0) to get, for each 25 m cell, the standard deviation of altitudes among the neighbouring cells at 500 m distance. These data were averaged and matched with 10 km x 10 km grid cells in the IP.

Finally, data on current organic carbon stocks in soils at 1 km2 resolution were obtained from Yigini & Panagos, (2016) (available at https://esdac.jrc.ec.europa.eu/content/soil-organic-carbon-soc-projections-europe#tabs-0-description=1; date: 29 July 2021). In parallel, data on carbon sequestration by forests and woodlands were obtained from

Vallecillo et al., (n.d.) at 1 km2 resolution (available at http://data.europa.eu/89h/3509c9d0-a51f-4bce-8b02-e1738e7ffc2d; date: 29 July 2021). The two original maps, were averaged into the 10 km x 10 km grid cells of the IP. The sequestration of carbon by forests and carbon reservoirs are an ecosystem service that can contribute to mitigate greenhouse emissions. According to the United Nations Economic Commission for Europe (UNECE), in 2004, EU28 forests contains 9.8 billion tons of carbon (tC) and the total carbon emissions of the EU28 was 1.4 billion tons of carbon (Carbon Sinks and Sequestration | UNECE, n.d.). The assessment of the areas where forests take and restore more carbon of the atmosphere, makes it possible to determine the areas that can contribute to mitigating the effects of climate change and their impacts in the biodiversity.

Data Analysis
Climate change impact assessment

Although the study focused on the IP region, it is important to understand how climate change impacts in IP compares with the ones expected for EU28. First, I calculated the average climatic suitability, species-wise, for each time period and RCP, for the whole EU28 and in grid cells where each species presently occurs at the scale of EU28, IP and Iberian PAs. Second, for each species, the persistence associated to each occurrence grid cell (product of suitability scores through time) was computed to assess if the occurrence areas will keep the climate conditions over the years. The maps that represent that information were made for species predicted to lose range in the IP, by Sousa-Guedes et al., (2020): *I. monticola* and *C. lusitanica*. Third, to assess the relative performance of current PAs, suitability values in PAs were compared to suitability values of a random set of areas among the IP (of equivalent total surface), for each time period and RCP (using R-CRAN packages "*foreign*", "*rio*" and "*readr*").

Finally, to anticipate climate threats over species, I assessed the type and magnitude of climatic suitability changes where species currently occur and in corridors. Suitability trend types describe how the climatic suitability value will evolve. One can infer possible effects of suitability oscillations through time over species persistence (Early & Sax, 2011). Magnitudes of change quantifies suitability shifts between the baseline period and 2080. I started this analysis by creating groups of possible trends: one with a homogenous type of change (Group B) and three others with distinct types of heterogeneous changes (Group A, C and D). Heterogeneous trend can be positive or negative, whether the final year's suitability value is higher or lower from the first year:

- Group A: the climate suitability values are equal between two consecutive periods. **An** if the final year's suitability value is smaller than the first year's, **Ap** if the final year's suitability value is higher than the first year's;
- Group B**:** the net variation of the climate suitability values is zero. Suitability can vary between periods, but the last year's value is equal as the first year.
- Group C: the climate suitability values are equal in three consecutive periods. **Cn** if the final year's suitability value is smaller than the first year's, **Cp** if the final year's suitability value is higher than the first year's;
- Group D: the climate suitability values are always different between consecutive time periods. **Dn** if the final year's suitability value is smaller than the first year's, **Dp** if the final year's suitability value is higher than the first year's.

Figure 4 provides some examples of qualitative and quantitative suitability trend:
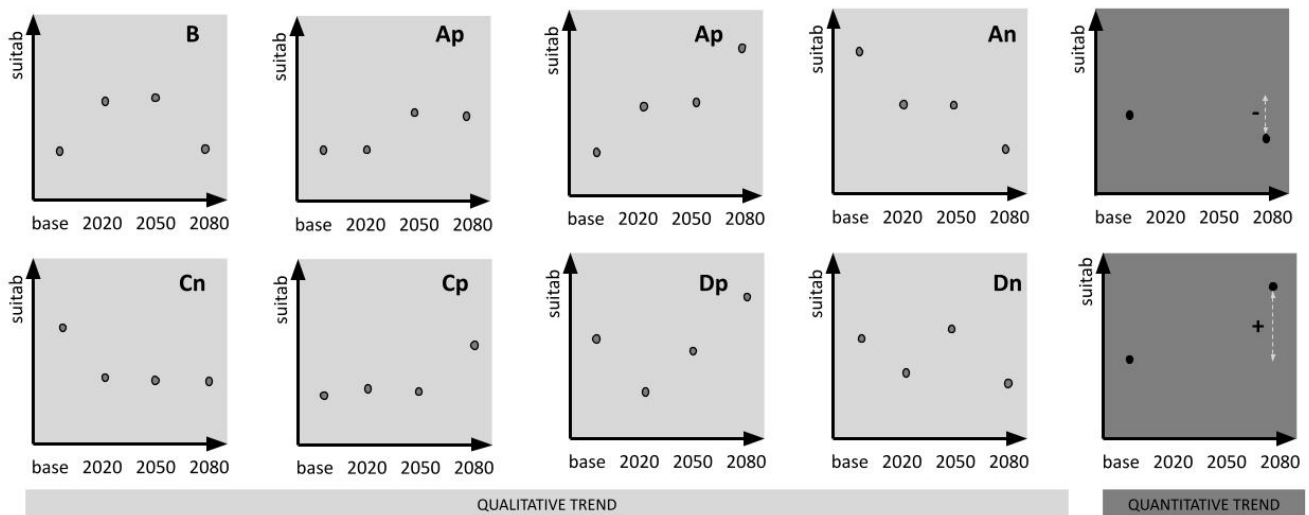
Figure 4 Examples of each suitability trend type (qualitative trend, on the left) and magnitude of suitability trend (quantitative tre nd, on the right).

I assessed what is the most common form of climate suitability evolution, obtaining the proportion of each suitability trend type at the occurrence sites of each species in the IP. I also tested whether trend types in species occurrence area were significantly different from the remaining area in the IP, PAs and whole EU28. Then I repeated the analysis to compare trend types of grid cells that belong to the corridors with trend types of the IP, occurrence areas, Iberian PAs and EU28. For each comparison, I performed Pearson's chi-squared tests using the function "*chisq.test*" from package "*stats*" in the R-CRAN. Each analysis was repeated for each RCP.

Significant differences of magnitude changes were assessed between all occurrence cells and the whole IP, Iberian PAs and EU28 and between corridor cells and the IP and EU28. Because data did not follow a Gaussian distribution nor presented homogeneous variances (confirmed through histograms and Bartlett test, respectively (Legendre &

Legendre, 2012)), the non-parametric Wilcoxon test was applied. The Wilcoxon test is also adequate to analyse nested data, as the one here analysed (i.e., Iberian PAs against the whole IP) (Zimmerman & Zumbo, 2010). Each analysis was repeated for each RCP using function "*wilcox.test*" from package "stats" in R-CRAN.

Corridor characterization

In order to analyse the spatial patterns of corridors over time, I: a) counted, for each species, the number of corridors converging in each grid cell in each time period, providing a measure of centrality of grid cells for the adaptation of species to climate change; b) counted the total number of corridors converging in each grid cell, among the analysed species, thus evaluating the general adaptive value of areas for the whole set of species; c) averaged the persistence scores associated to the corridors of all species and; d) counted the total number of species whose top persistence corridors cross each grid cell.

To determine what might best characterize the ability of some areas to be part of adaptive corridors, corridor counts in grid cells were regressed against the four landscape descriptors: a) Land-use classes (artificial surfaces; artificial green structures; homogeneous agriculture; heterogeneous agriculture; forest and semi-natural land, and; continental waters); b) Human pressure on the environment through the HF); c) topographical roughness; and d) carbon retention (soil and forests).

To assess the relationship of each landscape descriptor with corridor performance, I undertook two analyses: a) univariate regression models and b) Wilcoxon test, using functions "*lm*" and "*wilcox.test*" from package 'stats' in R-CRAN.

Results

Climate change impact assessment in Europe and IP

Among the analysed species *C. lusitanica* presents the largest suitability conditions along the whole EU28 and among occurrence areas (see Fig. 5b for RCP 6.0 and Tables 1-4 in Annexe IV for the remaining RCPs). Contrarily, *I. monticola* is the species with the lowest suitability scores in occurrence areas in the four time periods. The occurrence areas of *C. bedriagai,* climatic conditions will favor this species by 2080, when compared to baseline. At the scale of EU28, climatic suitability for *R. iberica, Galemys pyrenaicus* and *M. cabrerae* is expected to be the lowest ones. Here, on average, climatic conditions by 2080 will favor *P. cultripes, M. leprosa* and *L. schreiberi*, when compared to climate in the baseline period (Fig. 5a). For all species, suitability trends in occurrence areas will decrease uniformly over time, while in the overall EU28, no particular pattern is verified.
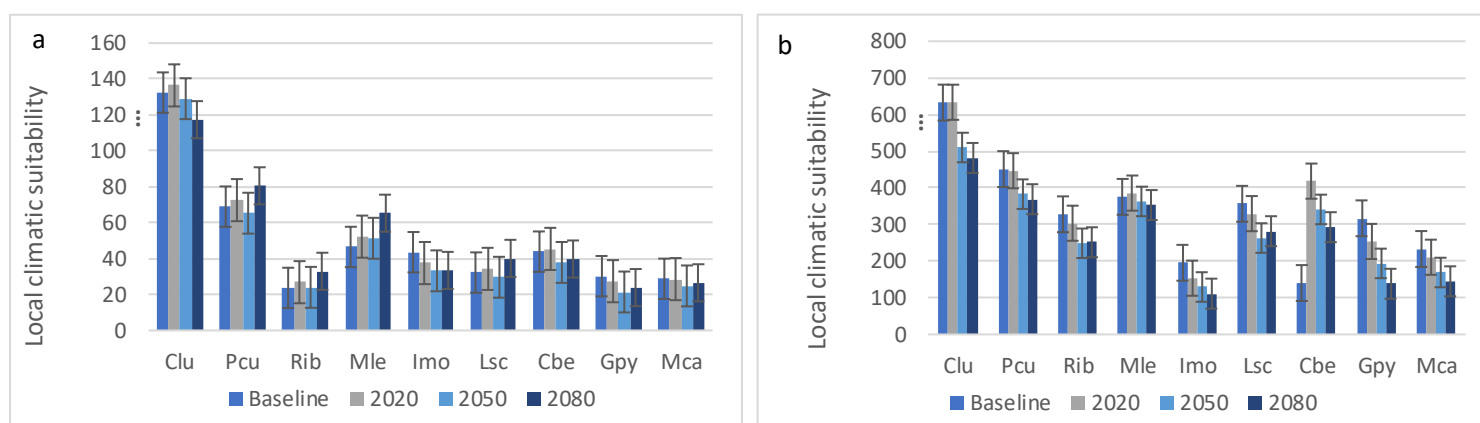
Figure 5 Climatic suitability scores across EU28 (a) and where species occur in EU28 (b) in RCP 6.0. Error lines represent coefficients of variation among RCPs, *Clu- Chioglossa lusitanica, Pcu- Pelobates cultripes, Rib- Rana iberica, Mle-Mauremys leprosa, Imo- Iberolacerta monticola, Lsc- Lacerta schreiberi, Cbe- Chalcides bedriagai, Gpy- Galemys pyrenaicus, Mca- Microtus cabrerae.*

The whole set of occurrence areas for species in IP show, in average, higher climatic suitability than protected occurrence areas in IP (Fig. 6). Differences in suitability in baseline vary from 139 (*C. bedriagai)* to 632 (*C. lusitanica)* in IP and from 44 (*C. bedriagai*) to 135 (*P. cultripes*) in PAs (Fig. 6b). However, comparing the trend of the average suitability between baseline and 2080, there is a negative trend, with the exception of *C. bedriagai*. Though, in PAs the occurrence areas of C. *lusitanica* and *C. bedriagai* experienced an increase in climatic suitability from the baseline period to 2020, with the increase verified by the latter species being particularly meaningful (i.e., a three-fold rise) (Fig. 6a).

See Annexe V (Fig. 2 and 3) for the distribution of the climatic suitability scores of each species for each RCP in IP and in Iberian PAs.
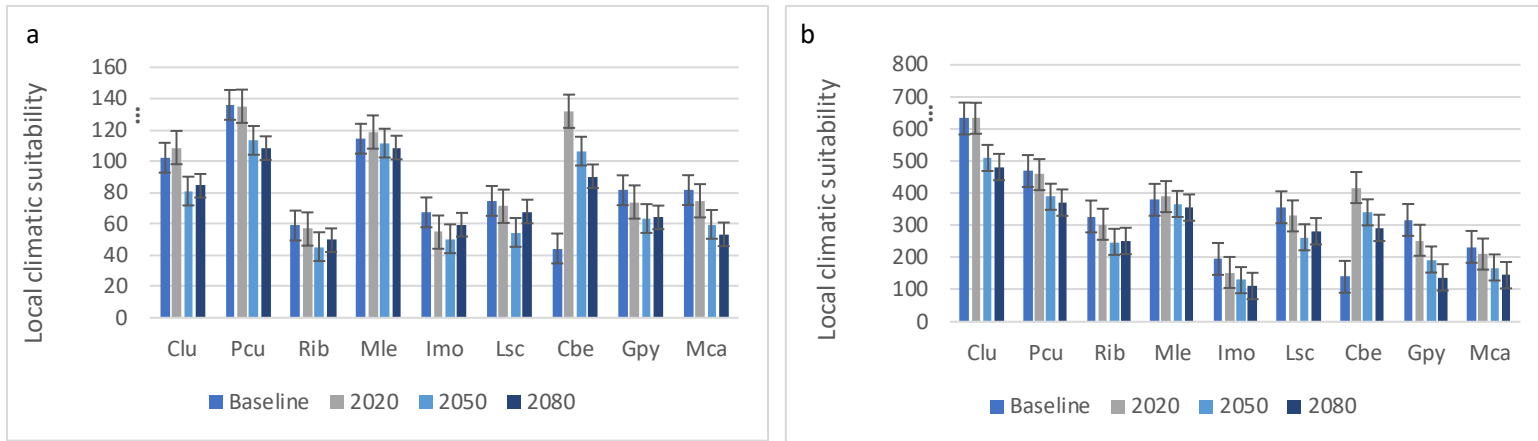
Figure 6 Average climatic suitability of occurrence sites in Iberian PAs (c) and occurrence sites in IP (d) in RCP 6.0. Error lines represent coefficient of variation among RCPs. Clu- *Chioglossa lusitanica, Pcu- Pelobates cultripes, Rib- Rana iberica, Mle- Mauremys leprosa, Imo- Iberolacerta monticola, Lsc- Lacerta schreiberi, Cbe- Chalcides bedriagai, Gpy- Galemys pyrenaicus, Mca- Microtus cabrerae.*

Persistence scores in occurrence areas

The occurrence sites persistence of *C. lusitanica* and *I. monticola* is present in Figure 7. These maps show the climatic suitability accumulated over the 90-years period of climate change predicted by RCP 6.0. *C. lusitanica* is going to lose a lot of its suitability within its limits of occurrence, as we can see by the lower order of magnitude of suitability scores ($6.95 \times 10^{10} - 6.00 \times 10^{11}$ against 8.35×10^{11} in top persistence areas) (Fig. 7a). The areas with higher persistence values are concentrated in the north and alongshore of the peninsula. *I. monticola* is the species that loses the most suitability in its occurrence sites: the areas with higher values are greatly reduced and fragmented (Fig.7b).
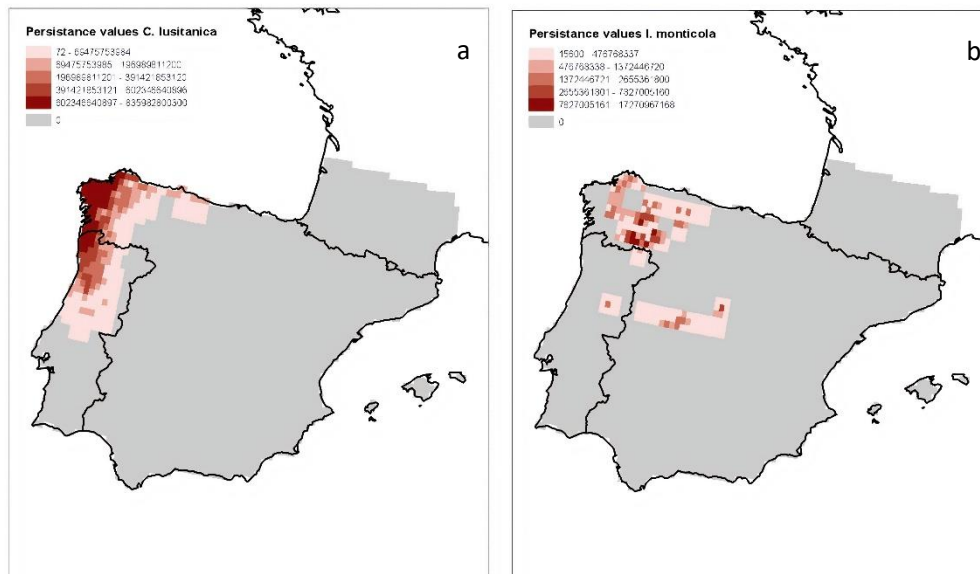
Figure 7 Persistence patterns of *C. lusitanica* (a) and *I. monticola* (b) in their respective occurrence areas.

Corridors' locations

For the set of species here analysed, the northwest of IP emerged as the hotspot for adaptive corridors (Fig. 8). The southwestern Portugal, the southeast of Spain (i.e., Almeria, Murcia and Alicante Provinces) and the northern part of Castilla y León province also have substantial numbers of corridors. There is a faint connection between the northwest and southeast corridors, linked by Castilla y León. In the region where more corridors converge, some PAs overlap.
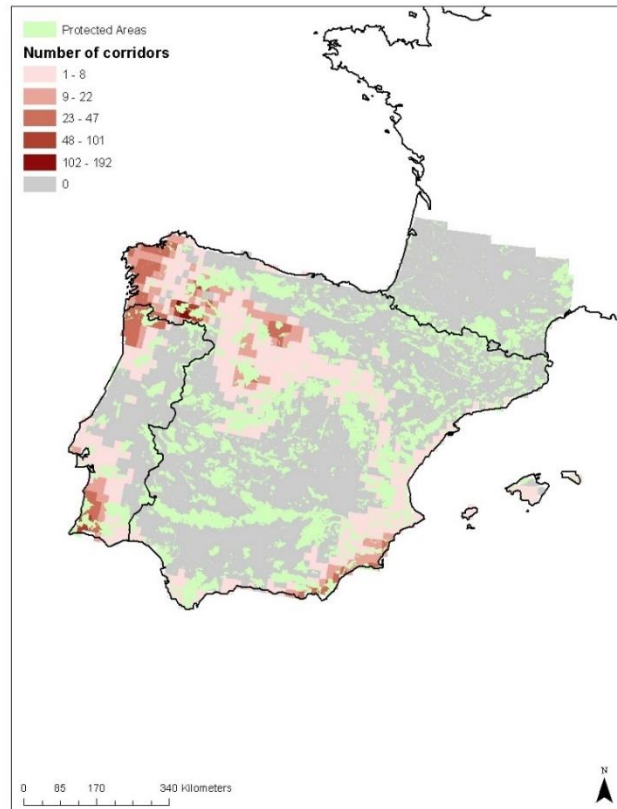
Figure 8 Counting's of corridors in each grid cell used by all species in RCP 6.0 and the location of all protected areas in Iberian Peninsula. Redder areas have more corridors.

Small areas spots in southern IP and Galicia will assist more than five species at different periods in time (Fig. 9). However, the ranking of hotspots varies, with the Castilla y León region occurring first in the baseline period and then in 2080. After 2020, more species start using corridors.
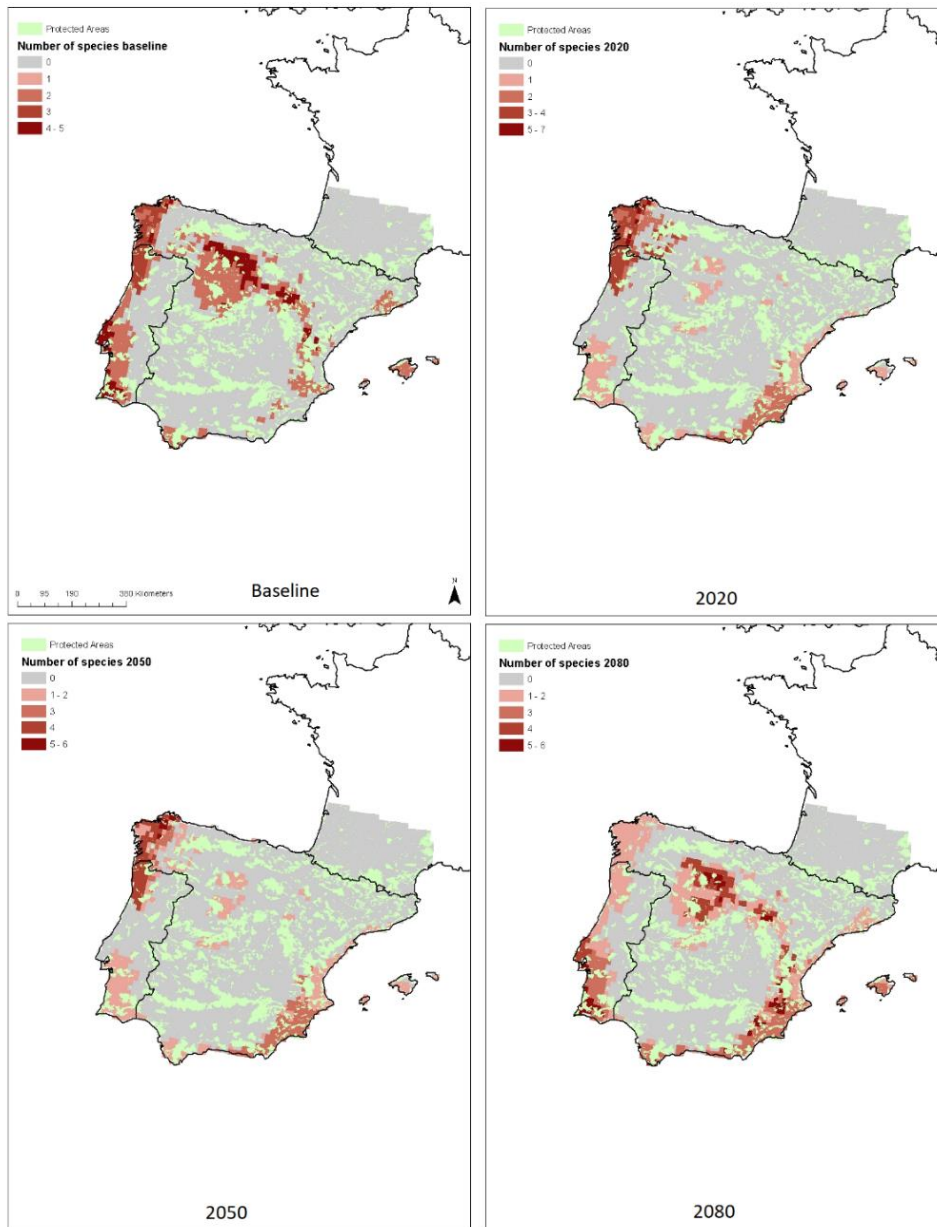
Figure 9 Number of species using each corridor in each grid cell. Location of protected areas.

In all periods, the northwest of IP is the region with the highest average persistence corridors (Fig. 10). But there are some changes over time. In the baseline period the western IP, particularly its northern segment, emerges as the one where the summed persistence scores of corridors are largest. With time, the connectedness of highlighted areas in this region decreases and new areas in the Castilla y León, Almeria, Murcia and Alicante regions arise. Importantly the top persistence areas by 2080 (i.e., summed persistence over 0.5) will assist the current set of species better than the top areas of other time periods.
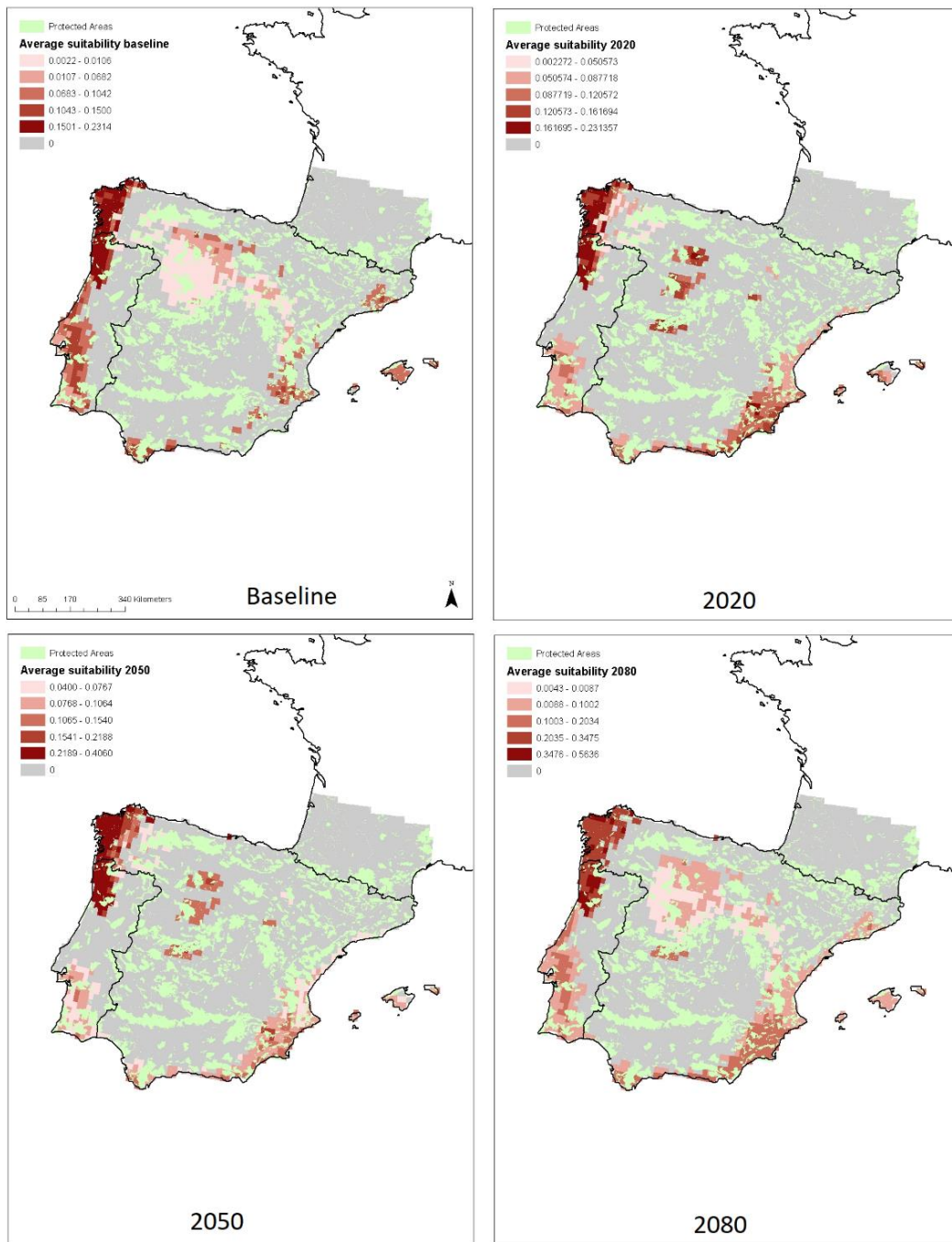
Figure 10 Average persistence of all corridors within each grid cell, in each period in RCP 6.0. Location of protected areas.

For the analysed species, the areas with more corridors (Fig. 11) are the northwestern IP (*I. monticola, L. schreiberi, R. iberica, C. lusitanica and G. pyrenaicus*), southwestern Portugal (*M. leprosa* and *P. cultripes)* and the southeastern region in Spain (*C. bedriagai).* The Castilla y León region and the southwest Portugal have more corridors for *M. cabrerae*. The coverage of corridors by Iberian PAs is not homogeneous among species, as some species experience better coverage of top corridors by PAs than others (i.e., *L.*

schreiberi, R. iberica and *C. lusitanica* have lower coverage of PAs in their adaptive corridors). The species with top corridors located at the northwestern IP are less covered by PAs.

The areas where the performance of the corridors is highest, either because of a large number of species using them (Fig. 9), either because of a few corridors with high suitability expectancies (Fig. 10), follows the general pattern of corridor density (Fig. 11).

Relative performance of current PAs

The relative performance of current PAs according to RCP 6.0 is presented in Table 3. For all climatic scenarios see Annexe VI. For most species the climate change effects within occurrence areas with Iberian PAs do not differ significantly from random sets of areas with overall size equivalent to PAs size. The exception is verified for *C. lusitanica*, for which PAs will perform worst in covering suitable climates from the baseline period to 2050 then random selected areas. A significant positive effect of PAs was only exhibited for *I. monticola* and *G. pyrenaicus* for 2080.

Table 3 Performance of PAs at occurrence sites in RCP 6.0. Comparison of random climatic suitability values with real climatic suitability values of protected areas in Iberian Peninsula at occurrence species sites: *Clu- Chioglossa lusitanica, Pcu- Pelobates cultripes, Rib- Rana iberica, Mle- Mauremys leprosa, Imo- Iberolacerta monticola, Lsc- Lacerta schreiberi, Cbe- Chalcides bedriagai, Gpy- Galemys pyrenaicus, Mca- Microtus cabrerae*. "-": the random climatic suitability model is better than the real climatic suitability model; "+": the random climatic suitability model is worse than the real climatic suitability model; "ns": the random climatic suitability model is the same as the real climatic suitability model.

	Clu	Pcu	Rib	Mle	Imo	Lsc	Cbe	Gpy	Mca
Base	-	ns	-	ns	ns	ns	ns	ns	ns
2020	-	ns	ns	ns	ns	ns	ns	ns	ns
2050	-	ns	ns	ns	ns	ns	ns	ns	ns
2080	ns	ns	ns	ns	+	ns	ns	+	ns

Suitability trend in occurrence sites

For most species, climatic suitability scores in occurrence areas will present a non-linear trajectory, with suitability by 2080 being lower than in the baseline period (designated **Dn** pattern) (Table 4). Though this type of impact oscillations (**Dn**) is dominant in these areas, for *I. monticola, G. pyrenaicus* and *M. cabrerae* another type of decreasing trend pattern occurs at a substantial fraction of occurrence areas, with a stability between two consecutive periods (An). For *G. pyrenaicus* and *M. cabrerae* the An pattern is dominant, while for *I. monticola both Dn and An patterns are dominant.*

Table 4 Percentage of each climatic suitability trend type at the occurrence sites of each species in the Iberian Peninsula in scenario RCP 6.0. The suitability type more frequent of each species is highlighted. *Clu- Chioglossa lusitanica, Pcu- Pelobates cultripes, Rib- Rana iberica, Mle- Mauremys leprosa, Imo- Iberolacerta monticola, Lsc-Lacerta schreiberi, Cbe- Chalcides bedriagai, Gpy- Galemys pyrenaicus, Mca- Microtus cabrerae.* An- climate suitability is equal between two consecutive periods. The final year's suitability is lower than the first year; Ap- final year's suitability is bigger than the first year; B- climate suitability can vary between periods but the last year is equal to the first year. Cn- climate suitability is equal between three consecutive periods. The final year's suitability is lower than the first year; Cp- final year's suitability is bigger than the first year; Dn- climate suitability is always different between consecutive time periods. The final year suitability value is smaller than the first year; Dp- - final year's suitability is bigger than the first year.

Species	Clu	Pcu	Rib	Mle	Imo	Lsc	Cbe	Gpy	Mca
An	17%	32%	17%	26%	**38%**	25%	23%	**54%**	**63%**
Ap	11%	5%	8%	12%	10%	9%	1%	8%	3%
B	1%	0%	1%	1%	1%	0%	1%	0%	1%
Cn	0%	0%	0%	0%	0%	0%	0%	0%	0%
Cp	0%	0%	0%	0%	0%	0%	0%	0%	0%
Dn	**43%**	**43%**	**49%**	**36%**	**37%**	**41%**	**62%**	24%	22%
Dp	28%	20%	25%	24%	14%	25%	13%	13%	11%

Comparison of suitability trend type in occurrence areas with PAs, IP and Europe

For all species, there are significant differences in the amount of suitability trend types between PAs and areas of occurrence (P-value < 0.05, Table 5). For *I. monticola* and *G. pyrenaicus,* the type **An** is more common in PAs than in occurrence areas (Dif. **An** < 0, Table 5) and for *L. schreiberi* and *M. cabrerae* the trend type **An** is more common in occurrence areas than in PAs (Dif. **An** > 0, Table 5). For *P. cultripes* and *M. leprosa* the symmetrical positive trend (**Ap**) is more dominant in PAs than in the occurrence areas. This same pattern is verified when comparing occurrence areas with the whole IP. A dissimilar pattern is obtained from comparisons of occurrence areas in IP with occurrence areas in EU28, where the dissimilar signal is mainly an effect of pattern **B** (i.e., similar suitability scores in baseline and 2080, with possible variation in-between those periods) being much more dominant in EU28 than in Iberian occurrence areas.

Table 5 Comparison based on Pearson's Chi-squared (statistic, p-value), between climatic suitability trend type at the occurrence sites of each species and: protected areas, Iberian Peninsula and Europe in RCP 6.0. The difference of proportions of each trend type between each location is also presented (Dif.). Highlighted numbers show for which species the difference is significant, based on a p-value < 0,05 and which trend type has a bigger difference between the two locations. Statistic- the value of the chi-squared test statistic. *Clu- Chioglossa lusitanica, Pcu- Pelobates cultripes, Rib- Rana iberica, Mle- Mauremys leprosa, Imo- Iberolacerta monticola, Lsc- Lacerta schreiberi, Cbe- Chalcides bedriagai, Gpy- Galemys pyrenaicus, Mca- Microtus cabrerae.*

Protected areas

Species	Statistic	P-value	Dif. An	Dif. Ap	Dif. B	Dif. Cn	Dif. Cp	Dif. Dn	Dif. Dp
Clu	490,450	**9,59E-103**	0,142	0,079	**-0,475**	-0,018	-0,057	0,299	0,029
Pcu	167,711	**2,25E-34**	0,070	**-0,133**	0,000	0,000	-0,002	0,075	-0,010
Rib	114,710	**4,14E-23**	0,106	-0,049	-0,020	0,000	-0,013	0,100	**-0,123**
Mle	238,752	**1,42E-49**	0,126	**-0,165**	-0,002	0,000	-0,011	0,131	-0,079
Imo	34,826	**4,66E-06**	**-0,095**	0,062	-0,051	0,000	-0,003	0,069	0,019
Lsc	49,164	**2,05E-09**	**0,091**	0,007	-0,024	0,000	-0,009	-0,031	-0,033
Cbe	201,482	**1,37E-41**	0,077	-0,104	-0,018	0,000	-0,003	**0,140**	-0,092
Gpy	148,083	**3,42E-30**	**-0,141**	0,050	-0,014	-0,054	0,000	0,089	0,071
Mca	185,647	**3,33E-38**	**0,291**	-0,173	-0,010	0,000	-0,007	-0,072	-0,030

Iberian Peninsula

Species	Statistic	P-value	Dif. An	Dif. Ap	Dif. B	Dif. Cn	Dif. Cp	Dif. Dn	Dif. Dp
Clu	451,465	**2,37E-94**	0,136	0,080	**-0,458**	-0,016	-0,054	0,282	0,030
Pcu	182,450	**1,60E-37**	0,071	**-0,139**	0,001	0,000	-0,001	0,075	-0,006
Rib	115,027	**3,54E-23**	0,103	-0,040	-0,021	0,000	-0,012	0,104	**-0,134**
Mle	243,674	**1,25E-50**	0,129	**-0,161**	-0,001	0,000	-0,009	0,123	-0,080
Imo	44,416	**6,11E-08**	**-0,111**	0,068	-0,053	0,000	-0,003	0,070	0,028
Lsc	48,445	**2,88E-09**	**0,086**	0,011	-0,026	0,000	-0,007	-0,022	-0,041
Cbe	209,526	**2,60E-43**	0,074	-0,102	-0,016	0,000	-0,002	**0,148**	-0,101
Gpy	175,151	**5,81E-36**	**-0,154**	0,054	-0,013	-0,052	0,000	0,088	0,077
Mca	192,541	**1,12E-39**	**0,292**	-0,178	-0,009	0,000	-0,006	-0,063	-0,036

Europe

Species	Statistic	P-value	Dif. An	Dif. Ap	Dif. B	Dif. Cn	Dif. Cp	Dif. Dn	Dif. Dp
Clu	2936,239	**0**	0,166	0,055	**-0,729**	-0,002	-0,055	0,396	0,170
Pcu	5854,668	**0**	0,290	-0,147	**-0,364**	-0,003	-0,053	**0,352**	-0,074
Rib	1883,922	**0**	0,148	-0,077	**-0,408**	-0,022	-0,165	**0,400**	0,124
Mle	4770,136	**0**	0,249	-0,118	**-0,334**	-0,002	-0,126	0,294	0,038
Imo	578,086	**1,24E-121**	0,307	0,043	**-0,560**	-0,005	-0,066	0,277	0,004
Lsc	1690,555	**0**	0,211	-0,039	**-0,460**	-0,011	-0,085	0,309	0,075
Cbe	3969,407	**0**	0,201	-0,086	**-0,535**	0,000	-0,051	0,506	-0,034
Gpy	1014,653	**6,05E-216**	**0,386**	-0,029	-0,356	-0,010	-0,063	0,127	-0,055
Mca	3613,324	**0**	**0,587**	-0,109	-0,436	-0,002	-0,104	0,139	-0,075

Comparison of suitability trend type in the corridors with occurrence areas, PAs, IP and Europe

The trend types **An** and **Ap** were the ones which most distinguished corridors from occurrence areas, Iberian PAs and the whole IP (Table 6). For all these cases **Ap** was always better represented in corridors than in each of the other sets of areas tested (Dif. **Ap** > 0, Table 6). By contrary, **An** was less represented in corridors comparing with the tested sets of areas (Dif. **Ap** < 0, Table 6). The trend type that most differentiates patterns in the whole EU28 from the ones within climate-adaptive corridors was **B**, because of the high representativeness of these patterns at the EU28 scale.

Table 6 Comparison based on Pearson's Chi-squared (statistic, p-value), between climatic suitability trend type of corridors of each species and: occurrence sites of Iberian Peninsula, protected areas, Iberian Peninsula and Europe in RCP 6.0. The difference of proportions of each trend type between each location is also presented (Dif.). Highlighted numbers show for which species the difference is significant, based on a p-value < 0,05 and which trend type has a bigger difference between the two locations. Statistic- the value of the chi-squared test statistic. *Clu- Chioglossa lusitanica, Pcu- Pelobates cultripes, Rib- Rana iberica, Mle- Mauremys leprosa, Imo- Iberolacerta monticola, Lsc- Lacerta schreiberi, Cbe- Chalcides bedriagai, Gpy- Galemys pyrenaicus, Mca- Microtus cabrerae.*

Occurence areas

Species	Statistic	P-value	Dif. An	Dif. Ap	Dif. B	Dif. Cn	Dif. Cp	Dif. Dn	Dif. Dp
Clu	229,91	**1,38E-48**	-0,157	**0,445**	-0,001	0,000	0,000	-0,287	0,001
Pcu	143,85	**2,72E-29**	**-0,205**	0,023	0,041	0,000	-0,001	0,011	0,131
Rib	350,56	**1,33E-74**	-0,158	**0,474**	-0,008	0,000	0,000	-0,321	0,014
Mle	360,59	**9,16E-76**	**-0,256**	**0,246**	0,033	0,000	0,013	**-0,215**	0,179
Imo	130,47	**3,08E-27**	-0,282	0,131	-0,003	0,000	0,000	-0,147	**0,302**
Lsc	366,74	**4,25E-78**	-0,218	**0,448**	-0,003	0,000	0,000	-0,259	0,032
Cbe	375,73	**5,03E-79**	-0,144	0,117	0,048	0,000	0,002	**-0,315**	0,292
Gpy	295,63	**8,69E-62**	**-0,449**	0,060	0,000	-0,004	0,000	0,072	0,321
Mca	287,45	**4,99E-60**	**-0,484**	0,016	0,118	0,000	-0,002	0,335	0,017

Protected areas

Species	Statistic	P-value	Dif. An	Dif. Ap	Dif. B	Dif. Cn	Dif. Cp	Dif. Dn	Dif. Dp
Clu	1150,37	**2,63E-245**	-0,015	**0,524**	**-0,476**	-0,018	-0,057	0,012	0,030
Pcu	169,64	**8,70E-35**	**-0,135**	-0,110	0,041	0,000	-0,003	0,086	**0,121**
Rib	465,08	**2,75E-98**	-0,052	**0,424**	-0,029	0,000	-0,013	-0,221	-0,110
Mle	122,48	**9,36E-25**	**-0,130**	0,080	0,031	0,000	0,002	-0,084	0,100
Imo	621,34	**5,82E-131**	**-0,378**	0,193	-0,055	0,000	-0,003	-0,078	**0,320**
Lsc	673,87	**2,19E-143**	-0,127	**0,455**	-0,027	0,000	-0,009	-0,290	-0,001
Cbe	117,00	**1,35E-23**	-0,067	0,013	0,030	0,000	-0,001	-0,175	**0,200**
Gpy	923,03	**2,75E-197**	**-0,590**	0,110	-0,014	-0,058	0,000	0,161	0,392
Mca	334,62	**3,57E-70**	-0,193	-0,157	0,109	0,000	-0,009	**0,263**	-0,013

Iberian Peninsula

Species	Statistic	P-value	Dif. An	Dif. Ap	Dif. B	Dif. Cn	Dif. Cp	Dif. Dn	Dif. Dp
Clu	1272,20	**1,13E-271**	-0,021	**0,525**	-0,459	-0,016	-0,054	-0,005	0,031
Pcu	190,03	**3,85E-39**	**-0,134**	-0,116	0,042	0,000	-0,003	0,086	0,125
Rib	532,70	**6,97E-113**	-0,055	**0,434**	-0,030	0,000	-0,012	-0,217	-0,121
Mle	130,00	**2,38E-26**	**-0,127**	0,084	0,032	0,000	0,004	-0,091	0,099
Imo	728,76	**3,77E-154**	**-0,393**	0,199	-0,056	0,000	-0,003	-0,077	**0,330**
Lsc	747,06	**3,27E-159**	-0,132	**0,459**	-0,029	0,000	-0,007	-0,281	-0,009
Cbe	114,99	**3,60E-23**	-0,070	0,015	0,031	0,000	0,000	-0,167	**0,191**
Gpy	1051,10	**5,19E-225**	**-0,603**	0,114	-0,013	-0,056	0,000	0,160	0,398
Mca	367,73	**2,66E-77**	-0,192	-0,162	0,109	0,000	-0,008	**0,272**	-0,019

Europe

Species	Statistic	P-value	Dif. An	Dif. Ap	Dif. B	Dif. Cn	Dif. Cp	Dif. Dn	Dif. Dp
Clu	2526,47	**0,00E+00**	0,009	0,500	**-0,730**	-0,002	-0,055	0,109	0,170
Pcu	1086,54	**1,70E-231**	0,084	-0,124	-0,324	-0,003	-0,054	**0,363**	0,057
Rib	878,12	**2,02E-186**	-0,010	0,397	**-0,416**	-0,022	-0,165	0,079	0,138
Mle	373,15	**1,65E-77**	-0,007	0,128	**-0,301**	-0,002	-0,113	0,079	0,217
Imo	978,91	**3,25E-208**	0,024	0,174	**-0,563**	-0,005	-0,066	0,130	0,306
Lsc	934,83	**1,11E-198**	-0,007	0,408	**-0,462**	-0,011	-0,085	0,050	0,107
Cbe	642,01	**2,02E-135**	0,056	0,031	**-0,487**	0,000	-0,049	0,191	0,257
Gpy	573,93	**9,79E-121**	-0,062	0,031	**-0,357**	-0,014	-0,063	0,199	0,266
Mca	1531,37	**0,00E+00**	0,103	-0,093	-0,317	-0,002	-0,106	**0,473**	-0,058

Magnitude of change in occurrence areas

The magnitude of change from the baseline period to 2080 did not vary significantly among species (Table 7). The species expected to present extreme changes are *G. pyrenaicus* and *C. lusitanica,* being largely penalized, in average, by climate change. *M. leprosa* was less impacted by the predicted changes.

Table 7 Summary of the magnitude values at the occurrence sites of each species in scenario RCP 6.0. n- sample size; mean; sd- standard variation; median; min- minimum; max- maximum; range; se- standard error. *Clu- Chioglossa lusitanica, Pcu- Pelobates cultripes, Rib- Rana iberica, Mle- Mauremys leprosa, Imo- Iberolacerta monticola, Lsc- Lacerta schreiberi, Cbe- Chalcides bedriagai, Gpy- Galemys pyrenaicus, Mca- Microtus cabrerae.*

Species	n	Mean	Median	Min	Max	Range
Clu	327	-154,113	-78	-734	538	1272
Pcu	1629	-98,4334	-120	-331	414	745
Rib	571	-76,345	-67	-497	492	989
Mle	1192	-24,3565	-34	-207	275	482
Imo	217	-84,1797	-123	-397	409	806
Lsc	703	-74,7909	-83	-532	504	1036
Cbe	1112	-123,255	-120	-372	234	606
Gpy	685	-178,769	-196	-771	621	1392
Mca	533	-88,1895	-86	-339	120	459

Comparison of magnitude of change in occurrence areas with PAs, IP and Europe

Except for *M. leprosa*, magnitudes of change of climate suitability in occurrence areas are lower than changes in protected occurrence areas in IP (i.e., PAs), the whole IP and EU28 (Table 8). Among species, those differences are particularly high for *C. lusitanica*. Differences between occurrence areas and the whole IP are essentially the same, but differences are significantly higher between occurrence areas in IP and the whole EU28 (i.e., suitability losses in EU28 are higher than in occurrence areas). Here, for some species differences in EU28 are double-higher than in IP and Iberian PAs (see *P. cultripes, I. monticola* and *C. bedriagai* in Table 8).

Table 8 Comparison between magnitudes of change of occurrence sites of each species and protected areas, Iberian Peninsula and Europe in scenario RCP 6.0, based on Wilcoxon test (statistic and p-value). Highlighted numbers show for which species the difference in the magnitudes of change at occurrence sites and other locations is significant, based on a p-value < 0,05. Statistic- Wilcoxon test statistic. Dif. mean- the difference of magnitude average between occurrence sites and other locations. Dif. median- the difference in suitability medians between corridors and other locations. *Clu- Chioglossa lusitanica, Pcu- Pelobates cultripes, Rib- Rana iberica, Mle- Mauremys leprosa, Imo-Iberolacerta monticola, Lsc- Lacerta schreiberi, Cbe- Chalcides bedriagai, Gpy- Galemys pyrenaicus, Mca- Microtus cabrerae.*

Protected areas

	Clu	Pcu	Rib	Mle	Imo	Lsc	Cbe	Gpy	Mca
Statistic	247582	1513717,5	447834,5	926444,5	157313,5	631691,5	913914,5	562539	407021,5
P-value	5,26556E-24	1,24761E-22	1,32E-30	3,2131E-53	8,73E-19	3,06E-17	1,72E-39	1,76E-28	2,46E-32
Dif. mean	-142,873695	-52,68339472	-69,291	-57,019988	-41,7122	-48,9034	-47,175	-91,2645	-45,7963
Dif. median	-78	-44	-71	-90	-105	-60	-48	-174,5	-44

Iberian Peninsula

	Clu	Pcu	Rib	Mle	Imo	Lsc	Cbe	Gpy	Mca
Statistic	299223	1767455,5	542299,5	1088342,5	186245,5	757868,5	1053036	668989	480379,5
P-value	3,89906E-22	4,56641E-26	4,57E-28	5,9329E-57	8,86E-19	9,02E-16	2,38E-46	2,95E-28	3,85E-33
Dif. mean	-135,724178	-54,94978816	-64,063	-58,369584	-40,2311	-43,7082	-49,6131	-87,7552	-46,1958
Dif. median	-78	-47	-71	-88	-106	-58	-52	-174	-44,5

Europe

	Clu	Pcu	Rib	Mle	Imo	Lsc	Cbe	Gpy	Mca
Statistic	2954439,5	8926773	4800152	12755161,5	1345962	6360914	3414603	4689256	2702938
P-value	2,22549E-52	0	1,75E-74	1,3581E-60	1,32E-57	6,32E-75	0	3,9E-132	3,6E-161
Dif. mean	-161,854811	-110,0157319	-85,6114	-43,137181	-82,3476	-82,6938	-119,144	-172,398	-85,9531
Dif. median	-78	-121	-67	-35	-123	-83	-120	-196	-86

Comparison of magnitude in corridors with occurrence areas, PAs, IP and Europe

Magnitudes of change in corridors are higher than in IP and EU28 (Table 9), except for *M. leprosa*, for which the changes are higher in IP and *P. cultripes*, *M. leprosa* and *M. cabrerae*, for which suitability changes in Europe are expected to be larger than in corridors.

Table 9 Comparison between magnitudes of change in corridors of each species and Iberian Peninsula and Europe in scenario RCP 6.0, based on Wilcoxon test (statistic and p-value). Highlighted numbers show for which species the difference between the magnitude of change in corridors and in others locations is significant, based on a p-value < 0,05. Statistic - Wilcoxon test statistic. Dif. mean- the difference of magnitude average between corridors and other locations. Dif. median- the difference in suitability medians between corridors and other locations. *Clu- Chioglossa lusitanica, Pcu- Pelobates cultripes, Rib- Rana iberica, Mle- Mauremys leprosa, Imo- Iberolacerta monticola, Lsc- Lacerta schreiberi, Cbe- Chalcides bedriagai, Gpy- Galemys pyrenaicus, Mca- Microtus cabrerae.*

Iberian Peninsula

	Clu	Pcu	Rib	Mle	Imo	Lsc	Cbe	Gpy	Mca
Statistic	1002970	820179,5	1003860	548420,5	1132351	1020176	933165	1097549	765143,5
P-value	1,66E-72	2,69E-15	1,28E-69	8,3E-11	4,583E-132	2,01E-76	7,167E-44	2,7E-113	6,085E-07
Dif. mean	145,017	23,56761	122,064	-31,021	94,9625842	164,5507	77,442325	139,5642	11,037666
Dif. median	162	84,5	163,5	-43	59	189	77	105	40,5

Europe

	Clu	Pcu	Rib	Mle	Imo	Lsc	Cbe	Gpy	Mca
Statistic	10823500	7846806	10913143	8928145	11442815,5	11269305	9269720,5	11159947	4033755,5
P-value	1,7E-111	0,013582	1,74E-80	2,63E-16	1,07E-115	1E-98	4,14E-26	5,37E-89	1,98E-73
Dif. mean	118,8863	-31,4983	100,5156	-15,7886	52,8460748	125,5651	7,9115438	54,92158	-28,71964
Dif. median	162	10,5	167,5	10	42	164	9	83	-1

Corridor characterization

The areas crossed by adaptive corridors present distinct abiotic and anthropic characteristics when compared with the areas not crossed by corridors (Table 10. See Fig. 4 in Annexe VII for the distribution of each factor in the IP). The corridors of *I. monticola* and *L. schreiberi* are richer in carbon in the soils than the remaining areas (Table 10, Linear Regression). The sequestration of carbon by forests is higher in the corridors of *M. leprosa, I. monticola* and *G. pyrenaicus* than in the remaining areas, but the opposite relationship was obtained for *C. lusitanica* and *P. cultripes*. For most species, there is a positive linear relationship between carbon sequestered by forest and number of corridors, although with small R2 (Table 10, Linear Regression).

Overall, corridors of all species present a larger topographical complexity than the remaining areas (Table 10, Wilcoxon). For all species but *C. lusitanica* and *C. bedriagai*, the areas with the largest number of corridors tend to have the least topographical complexity (Table 10, Linear Regression). However, the increase (or decrease) of the number of corridors of all species (except for *M. leprosa*) is poorly explained by this factor (high p-value slope).

Human pressure on the environment (human footprint) was found significantly different inside and outside of the corridors of almost all species but the linear relationship between this factor and the number of corridors varies among species (Table 10). For *L. schreiberi*, the increase in human footprint represents an increase in the number of corridors.

The areas covered by artificial surfaces is significantly different inside and outside of corridors of all species (except for *M. leprosa* and *M. cabrerae*) (Table 10). *G. pyrenaicus* has larger amounts of artificial structures in its corridors than in the remaining areas.

Agriculture was found significantly different inside and outside of the corridors for all species, but the type of production had different results depending on the species' corridors (Table 10). The linear relationship showed that the corridors of *M. leprosa, G. pyrenaicus* and *M. cabrerae* have more areas with homogeneous agriculture and the same pattern is verified for the areas covered by heterogeneous agriculture but only for *L. schreiberi's* corridors.

For all species there is a significant difference between the areas covered by forest and semi-natural land inside and outside corridors (Table 10). The corridors of *M. leprosa* and *G. pyrenaicus* have smaller areas covered by forests, but the corridors of *C. lusitanica, R. iberica and I. monticola* have higher areas covered by forests.

For the remaining land uses no particular patterns were obtained.

Table 10 Difference in soil organic carbon stocks on the environment, carbon sequestration by forests and woodland, topography, human footprint, area covered by artificial surfaces, heterogeneous and homogeneous agriculture, area covered by forest and semi-natural land, green urban areas and area covered by continental waters inside and outside corridors of each species, in scenario RCP 6.0, based on Mann-Whitney test (P-value). Highlighted numbers show for which species the difference of these factors inside or outside of the corridors is significant, based on a p-value < 0,05. Linear regression model (R2, Slope and P-value slope) between each factor and the number of corridors. Highlighted numbers show for which species these factors are relevant for the model, based on a p-value < 0,05. *R2- adjusted R-squared of the linear regression model*. Slope- estimated value of each factor for each added corridor. *Clu- Chioglossa lusitanica, Pcu- Pelobates cultripes, Rib- Rana iberica, Mle- Mauremys leprosa, Imo- Iberolacerta monticola, Lsc- Lacerta schreiberi, Cbe- Chalcides bedriagai, Gpy- Galemys pyrenaicus, Mca- Microtus cabrerae.*

CO2 soil

Species	Willcoxon P-value	Linear Regression R2	Slope	P-value slope
Clu	2,8E-10	0,032	-0,232	0,036
Pcu	3,2E-19	-0,005	-0,003	0,964
Rib	8,2E-01	0,049	0,560	0,000
Mle	6,1E-06	-0,003	-0,065	0,677
Imo	9,3E-01	0,031	0,505	0,002
Lsc	2,0E-42	0,075	0,733	0,002
Cbe	2,2E-02	0,044	-0,168	0,028
Gpy	2,7E-33	-0,002	0,185	0,365
Mca	3,4E-06	-0,004	-0,033	0,844

CO2 forests

Species	Willcoxon P-value	Linear Regression R2	Slope	P-value slope
Clu	1,4E-19	0,071	-1,076	0,00
Pcu	1,8E-47	0,057	-2,423	0,00
Rib	2,2E-11	0,057	5,567	0,00
Mle	1,3E-18	0,011	2,428	0,05
Imo	9,3E-11	0,031	4,714	0,00
Lsc	2,0E-44	0,239	3,926	0,00
Cbe	1,7E-08	0,014	-0,362	0,14
Gpy	1,7E-36	0,052	1,297	0,02
Mca	2,0E-21	0,001	1,422	0,27

Topography

Species	P-value	R2	Slope	P-value slope
Clu	1,1E-01	0,003	0,095	0,255
Pcu	6,9E-16	0,002	-0,131	0,232
Rib	1,2E-09	0,004	-0,251	0,145
Mle	7,1E-31	0,033	-0,522	0,002
Imo	5,0E-09	0,002	-0,242	0,207
Lsc	2,8E-02	-0,002	-0,150	0,385
Cbe	1,5E-01	-0,011	0,008	0,887
Gpy	1,1E-02	-0,010	-0,059	0,685
Mca	4,0E-33	0,004	-0,257	0,143

Human Footprint

Species	P-value	R2	Slope	P-value slope
Clu	6,1E-10	0,103	-0,081	0,00
Pcu	8,4E-07	0,154	0,371	0,00
Rib	1,0E-14	0,050	-0,464	0,00
Mle	6,5E-01	0,004	0,135	0,15
Imo	1,4E-16	0,019	-0,335	0,01
Lsc	7,1E-10	0,063	0,393	0,00
Cbe	3,7E-15	0,036	-0,028	0,04
Gpy	3,2E-10	0,162	0,452	0,00
Mca	5,6E-01	0,005	0,153	0,14

Artificial surfaces

Species	P-value	R2	Slope	P-value slope
Clu	8,5E-05	0,042	0,000	0,020
Pcu	8,5E-06	0,103	0,002	0,000
Rib	1,4E-10	0,023	-0,003	0,007
Mle	4,1E-01	-0,003	0,000	0,711
Imo	2,3E-12	0,009	-0,002	0,060
Lsc	2,2E-06	0,009	0,002	0,155
Cbe	2,3E-06	0,006	0,000	0,222
Gpy	1,8E-07	0,045	0,003	0,026
Mca	4,0E-01	-0,002	0,001	0,524

Heterogeneous agriculture

Species	P-value	R2	Slope	P-value slope
Clu	2,7E-05	0,028	-0,002	0,05
Pcu	2,8E-07	-0,005	0,000	0,71
Rib	2,5E-05	0,004	0,002	0,16
Mle	4,2E-36	0,003	-0,002	0,20
Imo	3,1E-05	-0,003	0,001	0,58
Lsc	1,6E-26	0,048	0,005	0,01
Cbe	1,2E-01	-0,009	0,000	0,64
Gpy	2,4E-22	0,011	0,002	0,16
Mca	1,9E-32	0,011	-0,003	0,04

Homogeneous agriculture

Species	P-value	R2	Slope	P-value slope
Clu	2,3E-42	0,004	-0,001	0,241
Pcu	1,2E-18	0,062	-0,011	0,000
Rib	5,3E-01	0,048	-0,011	0,000
Mle	1,4E-30	0,034	0,015	0,002
Imo	6,6E-01	0,050	-0,012	0,000
Lsc	1,5E-49	0,027	-0,002	0,040
Cbe	5,8E-34	0,030	-0,001	0,058
Gpy	6,2E-42	0,103	0,002	0,001
Mca	1,0E-31	0,041	0,018	0,001

Area covered by forests

Species	P-value	R2	Slope	P-value slope
Clu	1,8E-23	0,037	0,002	0,03
Pcu	3,4E-10	0,005	0,004	0,16
Rib	1,3E-04	0,039	0,011	0,00
Mle	6,8E-12	0,039	-0,015	0,00
Imo	2,1E-04	0,021	0,010	0,01
Lsc	5,0E-07	0,023	-0,006	0,05
Cbe	5,2E-30	0,014	0,001	0,14
Gpy	1,6E-05	0,104	-0,008	0,00
Mca	3,6E-13	0,048	-0,017	0,00

Green urban areas

Species	P-value	R2	Slope	P-value slope
Clu	2,32E-02	-0,007	0,000	0,639
Pcu	2,47E-01	0,078	0,000	0,000
Rib	2,29E-15	-0,003	0,000	0,734
Mle	6,08E-01	0,004	0,000	0,160
Imo	5,87E-15	0,000	0,000	0,320
Lsc	6,09E-01	-0,001	0,000	0,355
Cbe	1,56E-02	NA	0,000	NA
Gpy	8,32E-01	-0,009	0,000	0,662
Mca	7,94E-01	0,010	0,000	0,060

Area covered by continental waters

Species	P-value	R2	Slope	P-value slope
Clu	3,4E-01	0,141	0,000	0,00
Pcu	2,8E-03	-0,003	0,000	0,50
Rib	9,5E-01	-0,003	0,000	0,70
Mle	1,1E-04	0,002	0,000	0,21
Imo	8,0E-01	-0,004	0,000	0,90
Lsc	2,4E-02	-0,008	0,000	0,78
Cbe	1,9E-01	0,049	0,000	0,02
Gpy	1,0E-02	-0,007	0,000	0,52
Mca	2,7E-03	0,000	0,000	0,32

Discussion

This study demonstrates that future climate in EU28 and IP, up to 2080, will not favour the persistence of the analysed species under RCP 6.0, in particular in places where the Iberian populations occur today. Furthermore, the location of Iberian PAs does not contribute to protect climate adequacy any better than unprotected areas. Given this problematic scenario, the areas defining climate adaptive trajectories play a decisive role in maximising the persistence of species already under serious threat.

The low suitability across EU28 can be explained by the concentrated distribution of species within IP. Even in a changing climate, the evolution of climatic suitability across EU28 in a 90 years' period maintains the inadequacy to support the analysed species. Additionally, the evolution of suitable areas in IP for the studied species is not the same over the years - corroborated by Sousa-Guedes et al., (2020) — which poses a threat, as species may withstand declines in climate suitability, but variations before 2080 may prevent species from remaining where they occur. This threat should be considered in conservation actions against climate change, as the IP has changed greatly during the past periods of climate changes and several climatic scenarios predict that the Mediterranean Region is expected to undergo climate changes that exceed global average (Qin et al., 2013; United Nations Environment Programme/Mediterranean Action Plan and Plan Bleu, 2020), being one of the most responsive regions to climate change (Giorgi, 2006).

Given the results obtained, nature conservation and climate change mitigation measures are imperative (at least for the analysed species). The successful application of protection measures in natural habitats to reduce probability of species extinctions in the long term is confirmed by the Secretariat of the Convention on Biological Diversity, (2014), in particular when coordinated with the reduction of greenhouse gas emissions. Knowing that vertebrate species are shifting their geographical distributions into more suitable areas as a response to climate change (Hickling et al., 2006; Parmesan, 2006), and that most conservation actions are area-based (Aichi Target 11), the implementation of strict protection actions measures in core areas facilitates natural movement of species across the landscape, preventing further fragmentation of habitats, one of the most serious problems in nature conservation. However, **current Iberian PAs do not preserve climatic suitability for the species here considered any better than unprotected areas** and the top effective adaptive corridors have better climatic suitability when compared to PAs. This also demonstrates that current Iberian PAs may not be suitable in the face of climate change nor cover a great portion of climate adaptive pathways, proving that there is an urgent need to address this issue **in the location of new area-based conservation measures in the landscapes and in providing an upgraded management of already established PAs**. This outcome follows several other studies in which the low effectiveness of PAs worldwide to counter-back the

impacts of changing climates has been reported (Araújo et al., 2011; Loarie et al., 2009), with some of the studies concluding that PAs in the Mediterranean-Basin are likely to be largely unfavoured for many occurring species (Hoffmann et al., 2019). Further investigation should be conducted in order to determine what jeopardizes the effectiveness of Iberian PAs in climate change scenarios. Leverington et al., (2010) point to some of the most common problems that lead to inadequate PAs management: inadequate resourcing, inadequate communication and community relations, poor resource management and weak management planning, monitoring and research (namely on the condition and trend of PAs such as animal populations, forest condition, cultural values and socio-economic impacts). However, these measures alone are not enough to improve the climatic conditions in PAs during climate change. Addressing measures like the preservation of micro-refugia and habitat mosaic providing a greater variety of climate niches at the local scale, water management and riparian vegetation or shade with climate-resilient natural forest will help the management of areas that will endure during the climate crisis. Studies directed to Iberian PAs should be carried out so that these and other problems are identified and more adequate solutions to the IP are applied.

The correct choice of the best places to invest in conservation measures and, when possible, also implement mitigation actions against climate change defines one of the crucial steps in an effective and integrated policy for nature conservation. Prioritization of the areas to act or the species to protect is a necessary decision due to the limited resources available and the highly modified landscapes as in the IP. This study provides a possible guideline towards which are the most important Iberian areas for the studied species to adapt to climate change, and therefore where area-based conservation measures should be applied: northwest, south and center regions in IP. All these regions were also identified by Sousa-Guedes et al., (2020) as important refugia areas for reptile and amphibian species. An important outcome of this study is that species with a similar range of occurrence and habitat preferences ended up with climate adaptive pathways in the same regions. This information is useful for prioritising Iberian areas for nature conservation in the context of climate change, as the benefits associated to the local conservation efforts can be multiplied by several species – the ones exhibiting similar responses - facilitating and making more efficient the implementation of conservation measures. Furthermore, the focused analysis of *I. monticola* and *C. lusitanica* showed that these species are going to lose adequate climate conditions if dispersal does not occur. The regions where these species will occur in future time-periods were also identified by Sousa-Guedes et al., (2020) as important refugia areas for the same species (northwest). Although this region holds climatic suitability over the years, the adequate range area decreases. This result gives important clues about the need for a closer look at the species that occur in the same region.

Besides identifying the best areas to apply climate adaptation measures, information about landscape characteristics also helps to guide the application of adequate conservation measures. However, no apparent general pattern in the spatial distribution of the appraised factors over the location of top adaptive trajectories was found. Results varied among species, with some factors behaving positively or negatively with the adaptive value of areas. For example, topography and the area covered by continental waters did not present any significant relationship with the number of corridors, and factors like carbon reservoir in the soil, carbon retention by forests or area covered by forest had a negative relationship with the number of corridors of some species. But a positive relationship of these factors with the number of corridors of all species would be preferred as the areas with strong interest for the conservation are the ones with highly natural value and carbon retention. One the other hand, factors like artificial surfaces or human footprint undermine the conservation value of areas but some species had a positive relationship with the number of corridors. It should be considered however that these results express the relationships of the lowest order (linear) and therefore they provide information about a general correlative trend (thus resulting in low R2). In addition, several land use descriptors were grouped into one, for example homogeneous agriculture included various types of crops and techniques. A more adequate statistical analysis (GLMM) and a high-resolute analysis of the factors would contribute to determining more accurately how each factor relates to the conservation potential of each area that belongs to a corridor. Even so, these results show once again the need to improve the management of Iberian areas for climate change adaptation and mitigation.

In the framework applied here, some aspects were not accounted for. First, more species should have been included in the study in order to get a more comprehensive overview on area prioritisation in IP. Second, only one adaptive feedback of vertebrate species to climate change was addressed (spatial rearrangement). However, several other adaptation processes may exist, such as physiological and phenological (e.g., hibernation, aestivation and breeding). These processes have effects on population dynamics and persistence and are closely related to climatic conditions (Henle et al., 2008), therefore should be accounted for when impacts of climate change in biodiversity are analysed. Third, the dispersal of the species and the availability of suitable areas are influenced by many factors beyond climate and depend on the positive and negative interactions between the species and between the species and the environment (Atkins & Travis, 2010; Peterson et al., 2019). Furthermore, climate change itself alter these relationships. The inclusion of these complex ecological concepts was not possible, not only because it would be necessary many analytical and computational resources but also because of data deficiencies, namely on the dispersal capacities of species. Therefore, simplifications were inevitable but, depending on the aim of studies, they may be overcome in future works. Finally, the performance of national PAs and N2k

network could have been analysed separately. Araújo et al., (2011), Popescu et al., (2013) and Triviño et al., (2018) found a difference in the performance of these two types of conservation areas regarding their effectiveness in covering important areas for the conservation of some vertebrate taxa and plant species. A similar framework should have been conducted in the present study to assess if the same patterns are found in the IP.

It is worth mentioning that although ecological corridors are a useful measure to mitigate habitat fragmentation and help species track better climate conditions, it can also facilitate the dispersal of invasive species (and epidemic diseases). Because in some cases climate change will lead to the emergence or expansion of invasive alien species (Secretariat of the Convention on Biological Diversity, 2014), the risk of corridors facilitating their movement is high. This potential problem should be addressed when implementing actions in corridors. A study on the best location to implement the corridors (as done here), a careful management design, prior knowledge of the presence of exotic and invasive species in the region and control measures, and even a restoration of habitat (habitats in balance may hinder the installation of an exotic species) are actions that could prevent the widespread of invasive species facilitated by the corridors.

Some interesting results obtained here would be worthy to explore, but the aim of the study was to provide a brief overview of climatic trends and potential areas where more conservation focus is needed in IP under a biogeographic macro-scale view. In conclusion, mitigation actions to reduce the climate change impacts on Iberian biodiversity are needed. Efforts should be put in place to apply these measures in time, as the delayed application leads to more species losing their climatic range (Warren et al., 2013), being thus in the verge of local extinction. An important outcome of this work was that the areas of occurrence of the studied species will lose climatic suitability, and if they disperse to more suitable neighbouring areas, these areas will not be protected in the face of climate change (RCP 6.0). Ensuring landscape connectivity by protecting the pathways that lead to more suitable areas is a very useful measure not only to overcome this problem - especially for species with lower dispersal capacities - but also to mitigate landscape fragmentation. However, measures based only in changes in distributional ranges are not enough. Habitat restoration, creation and/or preservation of micro-refugia (very important in ectothermic species) or the establishment of dynamic PAs - PAs that can be implemented temporarily, in time and space, just to track the appropriate climatic conditions for species adaptation (as suggested by Alagador et al., (2014b) and Hoffmann et al., (2019)) may be important complementary conservation measures. Other measures may also include considering large PAs that encompass a heterogeneous set of environmental conditions (Araújo et al., 2004). This heterogeneity, not only climatic but also of habitats, will offer a diversity of resources that will

contribute to the adaptation of species to climate change, allowing a high level of functional communities and ecosystems. This view is supported by Hoffmann et al., (2019), who found that the PAs where climate change will be most critical, will be in the smaller PAs, located in regions such as in the Mediterranean-Basin. However, the fact that this is a heavily urbanized and fragmented area may lead to high challenges and attritions in implementing large and self-sustainable PAs. Even so, it is important to mention this knowledge, since, as far as possible, the implementation of measures that encompass greater environmental heterogeneity should be sought. The application of dynamic PAs can overcome the static applications of spatial conservation and the consideration of socioeconomic and cultural factors characterizing landscapes may attenuate conflicts for land use and optimise cost-effectiveness of conservation actions on the ground.

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Annexes

Annexe I

List of the plant species recorded at this stage:

- *Abies alba*
- *Taxus baccata*
- *Alnus glutinosa*
- *Carpinus betulus*
- *Quercus pubescens*

List of the vertebrate species recorded at this stage:

Amphibia

- *Alytes cisternasii*
- *Chioglossa lusitanica*
- *Euproctus asper*
- *Pelobates cultripes*
- *Proteus anguinus*
- *Rana iberica*
- *Rana latastei*

Reptilia

- *Chalcides bedriagai*
- *Elaphe quatuorlineata*
- *Emys orbicularis*
- *Lacerta schreiberi*
- *Mauremys leprosa*
- *Phyllodactylus europaeus*
- *Testudo graeca*
- *Testudo hermanni*
- *Vipera ursinii*
- *Iberolacerta monticola*

Birds

- *Acrocephalus paludicola*
- *Alcedo atthis*
- *Alectoris graeca*
- *Chersophilus duponti*
- *Falco biarmicus*
- *Falco cherrug*

- *Falco vespertinus*
- *Gallinago media*
- *Gypaetus barbatus*
- *Hieraaetus fasciatus*
- *Lagopus mutus*
- *Milvus milvus*
- *Neophron percnopterus*
- *Nyctea scandiaca*
- *Oenanthe leucura*
- *Podiceps auritus*
- *Pterocles orientalis*
- *Sylvia undata*
- *Tetrax tetrax*

Mammals

- *Galemys pyrenaicus*
- *Rhinolophus blasii*
- *Rhinolophus euryale*
- *Rhinolophus ferrumequinum*
- *Rhinolophus hipposideros*
- *Rhinolophus mehelyi*
- *Myotis bechsteinii*
- *Myotis blythii*
- *Myotis capaccinii*
- *Myotis dasycneme*
- *Nyctalus lasiopterus*
- *Barbastella barbastellus*
- *Plecotus austriacus*
- *Miniopterus schreibersii*
- *Spermophilus citellus*
- *Microtus cabrerae*
- *Mustela lutreola*
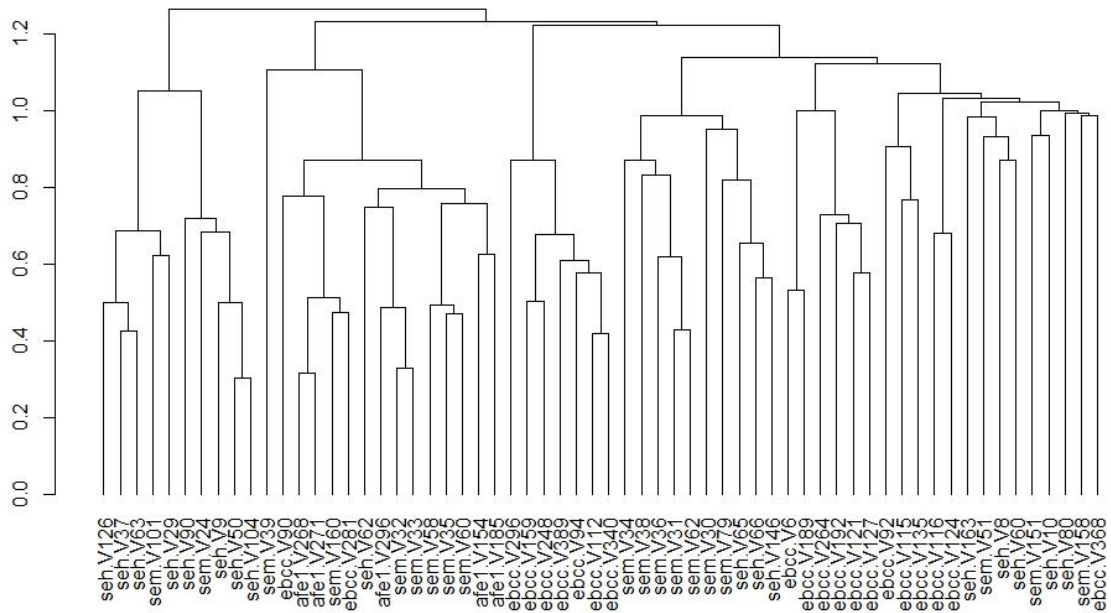- *Gulo gulo*
- *Lutra lutra*

Annexe II

Figure 1 Best cluster solution; x axis: species codes; y axis: Euclidean distance

Annexe III

The equations described by (Sutherland et al., 2000) estimate the maximum dispersal distance (in km) for a given mammal species using body mass in kg (M). The first equation (1) is for carnivore diet type and the second one (2) is for herbivores and omnivores diet type.

$$40{,}7 \times M^{0,81} \qquad (1)$$

$$3{,}31 \times M^{0,65} \qquad (2)$$

Despite the differences among mammal species, for instance reproductive ecology and movement capability, (Sutherland et al., 2000) found that "a significant proportion of the variation in the distances dispersed by juvenile mammals could be explained by differences in body mass and diet type".

Annexe IV

Table 1 Average climatic suitability of Europe. Clu- Chioglossa lusitanica, Pcu- Pelobates cultripes, Rib- Rana iberica, Mle- Mauremys leprosa, Imo- Iberolacerta monticola, Lsc- Lacerta schreiberi, Cbe- Chalcides bedriagai, Gpy- Galemys pyrenaica, Mca- Microtus

Species	Baseline	RCP 4.5			RCP 6.0			RCP 8.5		
		2020	2050	2080	2020	2050	2080	2020	2050	2080
Clu	132,4682	135,1476	126,0489	114,8487	136,4732	129,0586	117,3635	135,2945	125,5724	111,8997
Pcu	68,95307	73,26118	66,10836	78,5414	72,56862	65,3069	80,5354	72,68023	66,00298	84,97633
Rib	23,69334	27,22028	24,06105	30,24713	26,86028	24,01419	32,9597	26,70563	24,13481	34,41211
Mle	46,5012	52,68332	51,50313	61,17642	52,2475	51,33707	65,28184	52,1343	52,10525	69,92713
Imo	43,56841	38,01221	33,22872	35,09114	37,52901	33,21158	33,42473	37,66771	32,65591	31,64682
Lsc	32,24117	34,70272	30,01453	38,23809	34,28783	29,63506	40,14409	34,15624	29,78941	42,13525
Cbe	43,89255	45,70445	38,40994	40,17399	45,41089	37,87539	39,78101	45,45373	37,53002	40,03369
Gpy	30,23596	27,72798	21,79039	25,41722	27,4262	21,42775	23,86438	27,54614	21,27344	22,87136
Mca	28,77119	28,79198	25,17995	27,00417	28,59138	24,79889	26,53483	28,64363	24,86001	27,68453

Table 2 Average climatic suitability in protected areas of Iberian Peninsula at occurrence species sites. Clu- Chioglossa lusitanica, Pcu- Pelobates cultripes, Rib- Rana iberica, Mle- Mauremys leprosa, Imo- Iberolacerta monticola, Lsc- Lacerta schreib

Species	Baseline	RCP 4.5			RCP 6.0			RCP 8.5		
		2020	2050	2080	2020	2050	2080	2020	2050	2080
Clu	102,22	109,48	82,53	98,66	108,73	80,94	84,33	108,04	78,87	73,47
Pcu	135,99	135,71	115,25	116,19	135,12	113,32	108,36	134,89	111,44	103,54
Rib	58,92	57,39	46,14	53,40	56,70	45,44	49,55	56,44	44,90	46,25
Mle	114,38	119,34	113,04	112,80	118,64	111,57	108,74	118,36	110,61	105,77
Imo	67,34	54,69	49,29	65,36	54,71	50,47	59,45	53,88	49,74	44,67
Lsc	74,65	71,31	55,74	70,63	71,21	54,53	67,89	70,45	53,78	64,30
Cbe	44,27	133,02	109,48	99,62	131,91	106,44	90,40	131,41	103,31	83,61
Gpy	81,47	73,65	61,95	71,85	73,95	63,41	64,12	73,11	60,77	52,15
Mca	81,55	75,73	61,05	59,10	74,73	59,65	53,29	74,80	58,22	49,85

Table 3 Average climatic suitability in Iberian Peninsula at occurrence species sites. Clu- Chioglossa lusitanica, Pcu- Pelobates cultripes, Rib- Rana iberica, Mle- Mauremys leprosa, Imo- Iberolacerta monticola, Lsc- Lacerta schreiberi, Cbe- Chalcides bedriagai

Species	Baseline	RCP 4.5			RCP 6.0			RCP 8.5		
		2020	2050	2080	2020	2050	2080	2020	2050	2080
Clu	632,77	635,20	515,20	552,36	633,61	510,07	481,61	632,10	499,49	420,06
Pcu	469,33	460,41	396,16	397,36	458,11	389,15	370,90	457,64	383,37	355,52
Rib	327,82	303,57	250,58	272,46	303,45	248,74	251,48	302,36	246,01	230,40
Mle	379,76	391,68	372,64	369,46	389,65	366,79	355,40	388,78	363,43	346,81
Imo	195,54	153,87	128,30	139,84	153,50	129,48	111,36	152,52	123,59	85,71
Lsc	356,51	329,46	267,12	302,60	329,62	263,10	281,72	326,84	259,76	266,03
Cbe	139,86	421,20	349,41	319,98	417,91	340,64	292,24	416,40	331,17	271,09
Gpy	316,93	251,68	193,27	183,94	253,70	193,79	138,16	252,30	182,78	108,73
Mca	233,17	213,19	173,12	160,89	210,69	169,01	144,98	211,26	165,31	137,07

Table 4 Average climatic suitability in europe at occurrence species sites. Clu- Chioglossa lusitanica, Pcu- Pelobates cultripes, Rib- Rana iberica, Mle- Mauremys leprosa, Imo- Iberolacerta monticola, Lsc- Lacerta schreiberi, Cbe-Chalcides bedriagai, G

Species	Baseline	RCP 4.5			RCP 6.0			RCP 8.5		
		2020	2050	2080	2020	2050	2080	2020	2050	2080
Clu	632,77	635,20	515,20	552,36	633,61	510,07	481,61	632,10	499,49	420,06
Pcu	451,21	449,06	388,29	391,56	446,73	382,80	369,02	446,31	377,17	354,29
Rib	327,82	303,57	250,58	272,46	303,45	248,74	251,48	302,36	246,01	230,40
Mle	375,47	387,72	368,76	366,60	385,71	362,92	352,99	384,81	359,63	344,63
Imo	195,54	153,87	128,30	139,84	153,50	129,48	111,36	152,52	123,59	85,71
Lsc	356,51	329,46	267,12	302,60	329,62	263,10	281,72	326,84	259,76	266,03
Cbe	140,28	421,60	349,85	320,42	418,30	341,09	292,70	416,80	331,62	271,53
Gpy	316,93	251,68	193,27	183,94	253,70	193,79	138,16	252,30	182,78	108,73
Mca	233,17	213,19	173,12	160,89	210,69	169,01	144,98	211,26	165,31	137,07

Annexe V

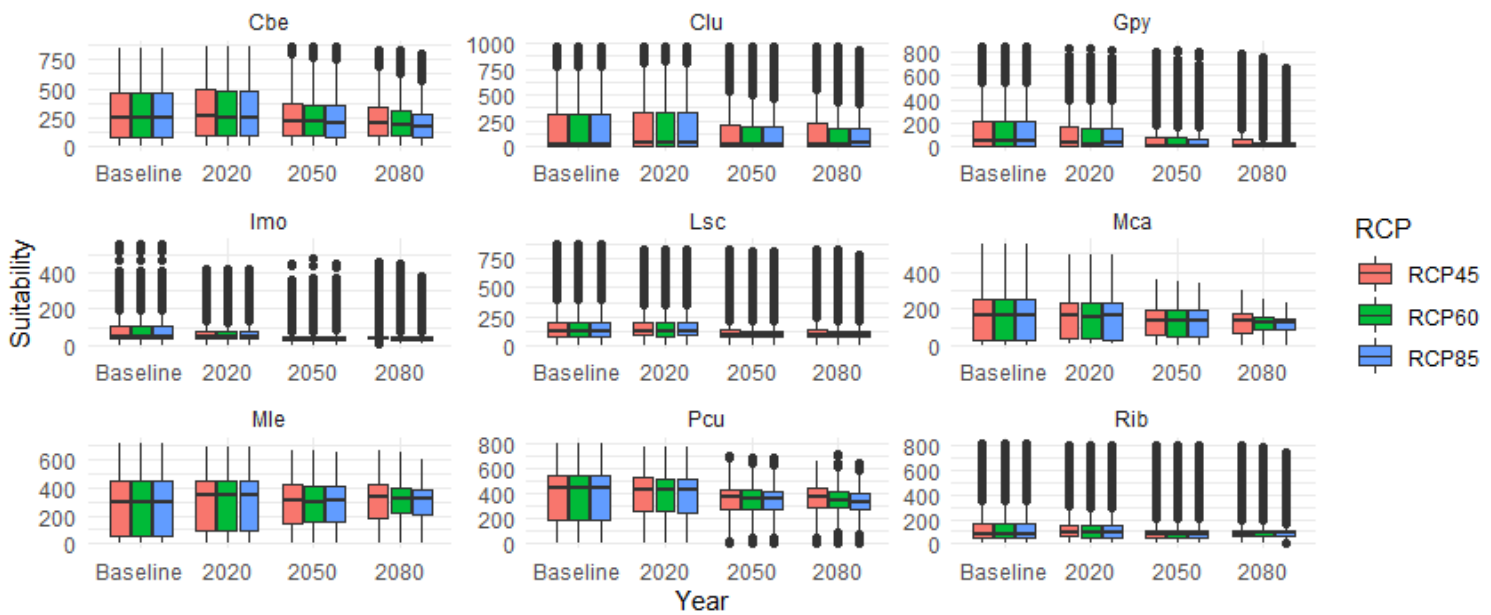Figure 2 Boxplots showing the variation of climatic suitability scores of each specie in protected areas in Iberia Peninsula under three emission scenarios (RCP 4.5, RCP 6.0 and RCP 8.5) by 1990 (baseline), 2020, 2050 and 2080. Climatic suitability scores are provided for all modelled species: Cbe- Chalcides bedriagai, Clu- Chioglossa lusitanica, Gpy- Galemys pyrenaica, Imo- Iberolacerta monticola, Lsc- Lacerta schreiberi, Mca- Microtus cabrerae, Mle- Mauremys leprosa, Pcu- Pelobates cultripes, Rib- Rana iberica.
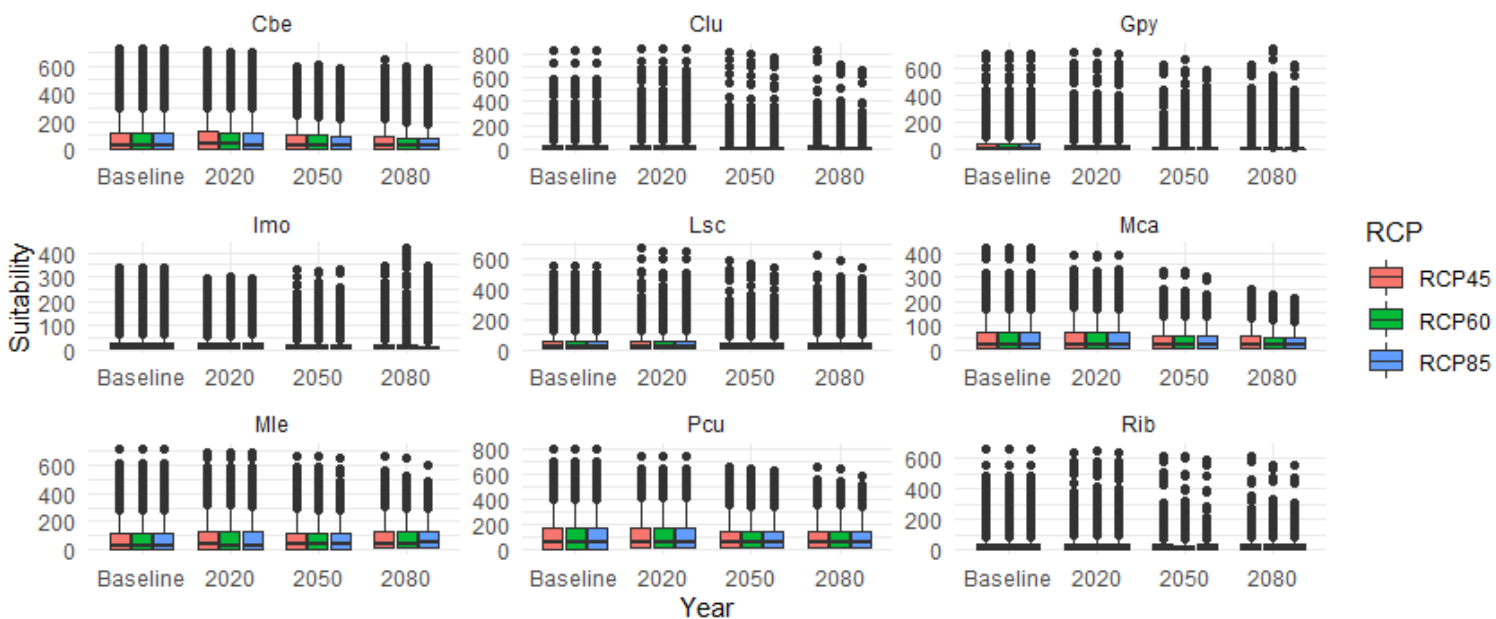

Figure 3 Boxplots showing the variation of climatic suitability scores of each specie in Iberia Peninsula under three emission scenarios (RCP 4.5, RCP 6.0 and RCP 8.5) by 1990 (baseline), 2020, 2050 and 2080. Climatic suitability scores are provided for all modelled species: Cbe- Chalcides bedriagai, Clu- Chioglossa lusitanica, Gpy- Galemys pyrenaica, Imo- Iberolacerta monticola, Lsc- Lacerta schreiberi, Mca- Microtus cabrerae, Mle- Mauremys leprosa, Pcu- Pelobates cultripes, Rib- Rana iberica.

Annexe VI

Table 5 Performance of protected areas at occurrence species sites. Comparation of random climatic suitability values with real climatic suitability values of protected areas of Iberian Peninsula at occurrence species sites: Clu- Chioglossa lusitanica, Pcu- Pelobates cultripes, Rib- Rana iberica, Mle- Mauremys leprosa, Imo- Iberolacerta monticola, Lsc- Lacerta schreiberi, Cbe- Chalcides bedriagai, Gpy- Galemys pyrenaicus, Mca- Microtus cabrerae. "-": the random climatic suitability model is better than the real climatic suitability model; "+": the random climatic suitability model is worse than the real climatic suitability model; "ns": the random climatic suitability model is the same as the real climatic suitability model.

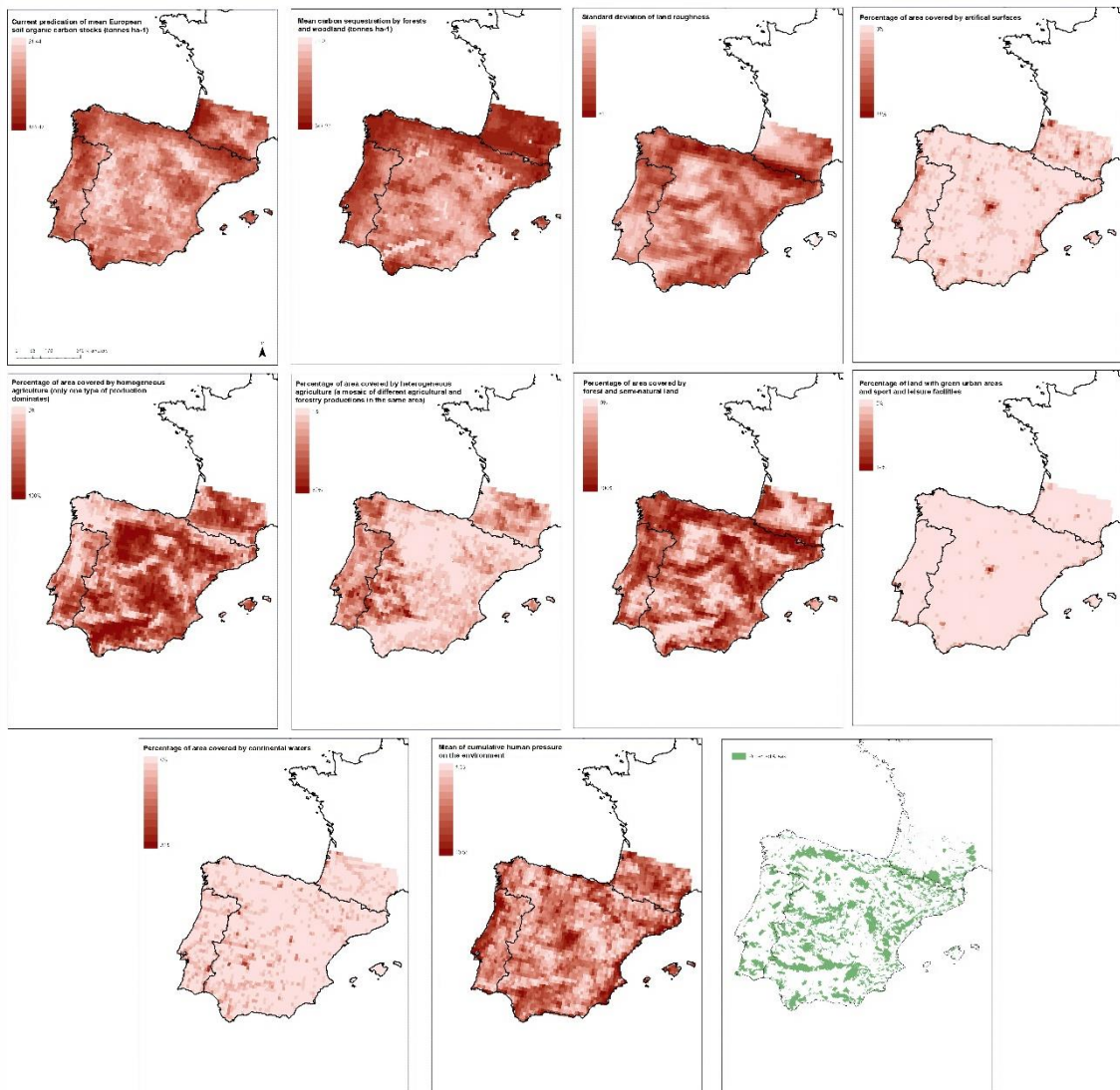|		Clu	Pcu	Rib	Mle	Imo	Lsc	Cbe	Gpy	Mca
	Base	**–**	ns	**–**	ns	ns	ns	ns	ns	ns
RCP 4.5	**2020**	**–**	ns	ns	ns	ns	ns	ns	ns	ns
	2050	**–**	ns	ns	ns	ns	ns	ns	ns	ns
	2080	ns	ns	ns	ns	ns	ns	ns	ns	ns
RCP 6.0	**2020**	**–**	ns	ns	ns	ns	ns	ns	ns	ns
	2050	**–**	ns	ns	ns	ns	ns	ns	ns	ns
	2080	ns	ns	ns	ns	**+**	ns	ns	**+**	ns
RCP 8.5	**2020**	**–**	ns	ns	ns	ns	ns	ns	ns	ns
	2050	**–**	ns	ns	ns	ns	ns	ns	ns	ns
	2080	ns	ns	ns	ns	**+**	ns	ns	**+**	ns

Annexe VII

Figure 4 Distribution of each factor in Iberian Peninsula. Map of protect areas in Iberian Peninsula.